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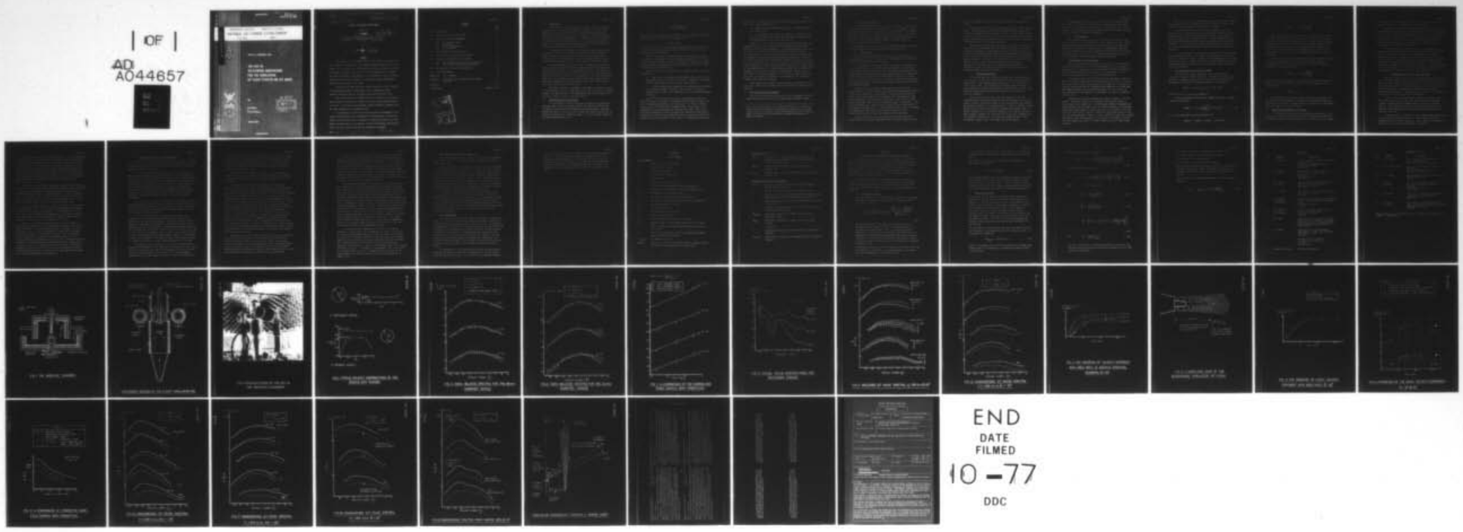

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THE USE OF CO-FLOWING AIRSTREAMS FOR THE SIMULATION OF FLIGHT EFFECTS ON JET NOISE

by

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B.J.Cocking

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6 The use of co-flowing airstreams for the simulation of flight effects on jet noise,

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10 D. J. Way [redacted] B. J. Cocking

SUMMARY

The simulation of 'in-flight' effects on aircraft noise continues to be the subject of much debate. One possible simulation consists of surrounding the air jet emitted from a stationary nozzle with a concentric secondary jet blowing at an appreciably lower velocity representing that of flight. This Report describes an investigation of the influence of such a co-flowing airstream on the noise of subsonic air jets over a range of secondary-to-primary area ratios from 1.8 to 1800.

Correlations of these data have confirmed that the effects of flight on jet mixing noise may be investigated using a comparatively small secondary stream and with the microphone positioned outside the flow.

The results show that a minimum area ratio of about 50 is necessary to model adequately the effects of flight for the main noise-producing regions of the jet. As the size of the secondary stream is reduced, information for the lower frequencies is progressively lost.

It is necessary to correct the flight data for the propagation of the sound through the shear layer surrounding the secondary flow. It has been shown that an existing theory is adequate for these corrections; this theory models the shear layer as a cylindrical velocity discontinuity and considers refraction of the sound as the dominant propagation mechanism.

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CONTENTS

1.0 Introduction

The continuing effort to quieten aero-engines requires an improved understanding of the noise sources present in flight. Since the levels measured from aircraft fly-over tests are made up from many different engine noise sources, these data are not suitable for the detailed study of individual noise-producing mechanisms. For exhaust noise, it is possible to eliminate, or at least alleviate, most of the problems by carrying out tests on rigs installed within a co-flowing stream so that the effects of flight are simulated under controlled conditions.

If these tests are performed in a wind-tunnel large enough for the microphone to be sited in the flow, the data may be readily corrected to flight conditions. Unfortunately few such facilities exist and they usually provide a less than perfect acoustic environment besides placing constraints on the range of jet and flight conditions that may be tested.

These disadvantages would be overcome if flight could be simulated using a co-flowing airstream of smaller diameter with the rig sited in an existing anechoic chamber; but this arrangement requires the microphone to be placed outside the airflow to remain in the far field of the noise source. Thus, corrections are required for the propagation of the sound through the shear layer of the flight-simulating stream. Past studies have indicated that these propagation effects are significant but only recently have the corrections been quantified theoretically.

This Report describes a programme of experimental and analytical work to investigate the validity of these theories and the use of small co-flowing streams for flight simulation. The experimental work has been restricted to the use of subsonic air jets as the noise source.

2.0 The position prior to this study

It can be shown[1,2,3] that the effects of flight on jet noise may be simulated using a stationary nozzle provided that both the nozzle and the microphone are placed within an extensive secondary airstream. The down-stream convection of the sound in the secondary flow may be corrected for by placing the microphone at a geometric angle, θ', to the jet axis, related to the sound emission angle, $\bar{\theta}$, by

$$\theta' = \tan^{-1}\left(\frac{\sin\bar{\theta}}{\cos\bar{\theta} + Ma}\right)$$

where Ma is the Mach number of the secondary flow. In addition, the measured frequencies should be modified by the Doppler factor

$$(1 + Ma\cos\bar{\theta})^{-1}$$

to correct for the lack of relative motion between the nozzle and the microphone. After these two corrections have been applied, the noise levels correspond to flight conditions.

Tests[2,3,4] have been conducted using this technique in the free jet of the RAE 24 ft wind-tunnel with the microphone traversed within the airstream. Although the range of operating conditions was limited, the results are still believed to represent the best information to date on the effects of flight on pure jet mixing noise.

The principal results from the tests for unheated subsonic jets may be summarised as:

1. The overall sound pressure level (OASPL) reduces in flight as approximately $V_{rel}^{5.4}$ at 90° to the jet axis. Larger noise reductions occur at angles approaching the jet axis in the rear arc.

2. Flight produces noise changes that are substantially independent of frequency for angles above 60° to the jet axis. At narrower angles, however, larger noise reductions occur for the lower-frequency jet noise.

Tests[5,6,7] have also been conducted to investigate the effects of flight on unheated jets using co-flowing airstreams of smaller diameter and with the microphone positioned in the ambient air. The results from the earliest tests of this type[5] were presented without corrections for the propagation of the sound through the secondary shear layer. That is, the noise levels measured on a fixed microphone were compared with and without secondary flow, and the noise changes were taken to represent the effects of flight on the jet noise emitted at this angle. Such measurements were made

by von Glahn et al using a rig with a secondary-to-primary area ratio* of 26. Their results may be summarised as:

1. OASPL reductions of approximately V_{rel}^{6} in 'flight' throughout the noise field.

2. Uniform noise reductions at all frequencies laterally to the jet axis, and larger noise reductions at the higher frequencies for angles approaching the jet axis in the rear arc.

Comparisons of the results from such tests with the wind-tunnel data highlighted[2] the need for additional corrections when small co-flowing streams are used for flight simulation. The differences between the results were believed to arise partly from a fundamental inability of small co-flowing streams to simulate fully the effects of flight, and partly from the propagation of the sound through the secondary shear layer. Theories have recently been developed independently by Amiet[8] and Jacques[1] to correct for this latter effect and these are discussed in some detail in this Report. A recent experimental study[6] indicates that the application of Amiet's theory to data measured outside the flight-simulating stream leads to an improved agreement with the results from the 24 ft wind-tunnel. However there is still need for a detailed examination of the validity of these shear layer corrections with particular emphasis on the minimum size of co-flowing stream to which they may be applied.

These aspects are discussed in greater detail in Section 6 after the acquisition of some additional data from a two-stream rig at NGTE has been described.

3.0 The test facility and programme

This Section describes the acquisition of the experimental data from a flight-simulating rig installed in the small anechoic chamber at NGTE.

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* The area ratios used in this Report have been calculated from the primary nozzle area and the area of uniform secondary flow at the primary nozzle exit (assuming that the potential core of the secondary stream forms a cone with a 7° half-angle). This definition has been adopted to allow a more meaningful comparison of data from rigs with different extensions of the primary nozzle downstream of the secondary flow exit plane.

3.1 The anechoic chamber

A diagram of the anechoic chamber is given in Figure 1; the floor is 5.2 m square and the height between wedge tips is 4.6 m. Wedges of glass fibre or polyurethane foam line the walls, floor and ceiling of the chamber and render it anechoic for frequencies above 250 Hz. Rigs are positioned centrally in the chamber and exhaust vertically to atmosphere through a hole in the roof. Air entrained from the chamber into the jet exhaust is replaced through vents in the walls.

Compressed air is supplied to the rig through three supply pipes, the mass flow through each being separately and remotely controlled.

3.2 The test rig

A sketch of the rig showing the air supplies to the primary and secondary nozzles is given in Figure 2, and a photograph of the installation in the anechoic chamber is shown in Figure 3.

It is important in the design of any rig intended to investigate jet noise to reduce as far as possible sources of extraneous noise generated within the air supply to the nozzle. This requirement becomes particularly stringent when flight-simulation tests are proposed since the secondary flow reduces the level of the jet noise and may unmask internal noise sources that are not discernible statically. To reduce the levels of internal noise in this rig, the primary flow was passed through a plenum chamber lined with sound-absorbing kaowool.

Primary nozzles of 22 mm and 86 mm diameter were tested with a secondary nozzle of 350 mm diameter, giving secondary-to-primary area ratios of 210 and 12 respectively. The secondary flow was supplied through two pipes to twin plenum chambers lined internally with noise-absorbing foam; pressure tappings connected from the supply pipes to the limbs of a water U-tube enabled the flows into the rig from each supply to be balanced. From the plenum chambers four pipes fed the air radially into an entry-section surrounding the primary nozzle. A fine gauze was placed across the secondary flow downstream of this section and this was followed by a short acoustically-lined duct to which the secondary nozzle was bolted.

The secondary nozzle exit was positioned 152 mm upstream of the primary nozzle so that noise measurements could be taken at angles of up to

120^{o} in the forward arc without significant shielding of the jet noise sources.

Total pressure traverses were taken across the exit of the secondary nozzle. These showed that a uniform flow had been achieved without any noticeable separation from the primary jet pipe. A typical radial traverse at a nominal secondary velocity of 75 m/s is shown in Figure 4a. After this initial calibration the secondary velocity was set from a pitot positioned at the mid-annulus of the secondary nozzle exit.

The two primary nozzles were calibrated for a range of subsonic jet velocities with a multi-point pitot rake placed at the nozzle exit plane. From these measurements a relationship was derived between the reference pressure in the primary plenum chamber and the mass-weighted total pressure at the nozzle exit. Typical velocity profiles measured for each nozzle are shown in Figure 4b. The profile for the smaller nozzle was basically flat whereas the larger nozzle had a more pronounced radial velocity distribution. This observation is not believed to invalidate the comparisons that will be drawn later between the static-to-flight noise reductions measured using the two nozzles.

3.3 Acoustic measurements

A 6 mm Bruel-and-Kjaer condenser microphone was traversed remotely on a polar arc of 2.09 m radius about the centre of the exit plane of the primary nozzle. Noise measurements were made at 15^{o} intervals from 30^{o} to 120^{o} to the jet axis. The microphone was calibrated regularly using a Bruel-and-Kjaer pistonphone and tones were injected into the circuit at the cathode follower at each $\frac{1}{3}$-octave centre frequency to calibrate the electronic equipment.

Third-octave analysis, with a 4 second integration time, was performed using a General Radio type 1921 real-time analyser. A frequency range of 250 Hz to 40 kHz was covered for the 86 mm primary nozzle and this was extended to 80 kHz for the smaller nozzle to allow for Strouhal scaling. The noise levels from the analyser were subsequently processed using a digital computer and corrections were applied at this stage for the microphone frequency response, the calibration of the electronic equipment and for atmospheric attenuation. The corrections ranged from zero at low frequencies to about 4 dB at the highest frequencies examined.

A Sangamo-Weston Sabre III tape recorder was used in parallel with the analyser. With suitable calibration this instrument recorded signals accurately up to 80 kHz, and thus allowed re-analysis of the noise data if required. No difference was evident between noise spectra analysed directly and those recorded and analysed subsequently.

3.4 Test conditions

Noise measurements were taken over a range of jet velocities from 190 m/s to 325 m/s. At the highest velocity the nozzle was slightly choked, and these data have been included only for angles near the jet axis where shock noise is believed to be insignificant. At each primary condition, polar noise traverses were taken at several secondary velocities from 0 m/s (the static datum case) to 75 m/s. In addition, measurements were taken of the noise produced from the secondary stream operated alone.

4.0 An assessment of the data quality

Before proceeding with the analysis of the data, it is necessary to establish the validity of the jet noise measurements. The first step in this process is to compare the noise levels measured without secondary flow with the generalised correlation curves[9] that have been derived from a consensus of experimental data for 'clean' model-scale jets.

Correlations of the relative $\frac{1}{3}$-octave spectra are shown in Figures 5 and 6 for the two primary nozzles at angles of 60^o, 90^o and 120^o to the jet axis. The scatter in the data measured in the forward arc is believed to be caused by reflections from the secondary plenum chambers, even though these were lagged externally with sound-absorbing foam. For this reason, the results presented in the remainder of this Report are limited to angles in the rear arc.

The measured and predicted OASPLs are compared in Figure 7 for both nozzles. The overall levels for the smaller nozzle typically agree to better than 1 dB with prediction. The differences between the measured and predicted OASPLs for the larger nozzle are somewhat greater and are probably caused by the measurements not being taken fully in the geometric far-field of the jet noise source, since the traverse for this nozzle was made at only about 24 nozzle diameters. However, a recent study[10] has shown that, although the absolute noise levels measured at this distance are slightly in error, the noise changes from static to 'flight' conditions are not significantly affected.

Thus, the static noise levels measured for both nozzles are believed to be dominated by pure jet mixing noise and to provide a suitable static datum with which to compare the noise levels in 'flight'.

The measurements with secondary flow were examined carefully to ensure that the noise generated by this stream did not interfere with the primary jet noise. Typical $\frac{1}{3}$-octave spectra obtained from running the secondary stream alone are shown in Figure 8. These 'background' noise spectra were subtracted from the measured spectra before the OASPLs were calculated. If the correction to any SPL was greater than 1 dB and that level contributed significantly to the OASPL, then the test condition was discarded.

It is very difficult to demonstrate conclusively that internal noise radiating from the primary nozzle remains insignificant when the jet noise levels are reduced in 'flight'. However, from an examination of the flight spectra, which show no obvious distortions, and from comparisons with other results where these can be made, there is no reason to doubt the validity of the data presented.

5.0 The correlation of the effects of flight

An expression derived in References 2 and 3 has been used to correlate the changes in OASPL from static to 'flight' conditions. This approach is an empirical modification of existing jet noise theory[11,12] and expresses the OASPL of an unheated subsonic jet in flight as:

$$\mathrm{OASPL}_\theta \propto 10 \log_{10} V_{rel}{}^m \, V_j{}^n \, (1 + \mathrm{Ma} \cos \bar{\theta})^{-1} \qquad \ldots.(1)$$

where the notation is defined in Appendix A.

From this expression the reduction in OASPL from static to flight conditions is given by:

$$\Delta\mathrm{OASPL}_\theta = 10 \log_{10} \left(\frac{V_j}{V_{rel}}\right)^m (1 + \mathrm{Ma} \cos \bar{\theta}) \qquad \ldots.(2)$$

or, if a modified OASPL reduction is defined as:

$$\Delta\mathrm{OASPL}'_\theta = \Delta\mathrm{OASPL}_\theta - 10 \log_{10} (1 + \mathrm{Ma} \cos \bar{\theta})$$

then,

$$\Delta OASPL'_{\theta} = 10 \log_{10} \left(\frac{V_j}{V_{rel}}\right)^m . \qquad ....(3)$$

This expression defines the reduction in OASPL in flight in terms of a relative velocity exponent, m, that varies only with angle. Extensive experimental data measured under conditions of simulated flight have given considerable justification to the use of this expression although small differences in the value of m have been observed between different jet noise rigs in much the same manner that unexplained discrepancies still exist between the static noise levels measured from different 'clean' jet facilities.

The effects of flight on the measured spectra are presented by extrapolating or interpolating the measured one-third-octave levels to standardised values for (V_a/V_j) of 0 and 0.20. To do this, Equation (3) has been used in the modified form,

$$\Delta SPL'_{\theta,f} = 10 \log_{10} \left(\frac{V_j}{V_{rel}}\right)^k \qquad ....(4)$$

where k is the velocity exponent at a particular frequency and angle. The value of (V_a/V_j) of 0.20 has been chosen so that this equation further simplifies to:

$$\Delta SPL'_{\theta,f} = k$$

Thus the spectral noise reductions to be shown will represent both the relative velocity exponent at the particular frequency and angle and the actual value of ΔSPL' in going from static conditions to a flight speed equal to 20 per cent of the jet velocity.

6.0 Discussion and presentation of results

It is intended in this Section to investigate the influence of the size of the co-flowing stream on the quality of the flight simulation and to assess the ability of the existing theory to correct noise data measured

outside the stream for the effects of the sound propagation through the secondary shear layer. The results are for unheated jets.

Laterally to the jet axis, propagation effects are believed[1,8] to be negligibly small. Thus a study of the data at 90° allows an assessment to be made of the minimum area of secondary flow that satisfies the aerodynamic requirements for flight simulation. Since the provision of a large but quiet secondary flow is one of the main experimental difficulties of flight-simulation studies, it is clearly of great interest to know the minimum size of this flow that may be used.

To extend the range of area ratios studied in the experiments, additional data have been extracted from various published sources[5,13,14]. Some of these tests were conducted to investigate the jet noise from externally-mixed by-pass engines under static conditions. These data have been restricted to test conditions with both airstreams unheated and with the primary flow subsonic; in addition the secondary velocity has been limited to a maximum of 0.2 of the primary velocity to prevent a contribution to the measured noise levels from the secondary stream. With the addition of these data the range of area ratios was extended down to 1.8.

6.1 The minimum area ratio for flight simulation

Typical $\frac{1}{3}$-octave spectra for a sound emission angle of 90° to the jet axis are shown in Figure 9 for a range of secondary-to-primary area ratios from 1.8 to 1800 (the wind-tunnel tests) and for various velocities of the flight-simulating stream. Although the general influence of area ratio can be seen, a more direct comparison may be made when the spectra are standardised to the values of (V_a/V_j) equal to 0 and 0.20. The estimated spectra at these velocities are shown in Figure 10.

Consider first the spectra measured from the wind-tunnel tests. Noise reductions occur in 'flight' that are substantially independent of frequency (although they are somewhat greater at the higher Strouhal numbers). These changes are believed to arise from a reduction of the shear across the jet mixing region accompanied by modifications to the structure of the jet.

As the area ratio is lowered, the noise changes brought about by the secondary flow are reduced, first at the lower frequencies and then progressively at the higher frequencies. These changes are quantified as a function of area ratio and Strouhal number in Figure 11.

The reason for the strong frequency dependence of the noise reductions at the lower area ratios becomes clear from Figure 12 which illustrates the structure of a jet surrounded by a small secondary airstream. The part of the jet near the nozzle exit (region A) is adequately sheathed within the potential core of the secondary flow. Further downstream (region B) the mixing region of the secondary stream with the ambient air has penetrated inwards to meet the mixing region of the primary jet, so altering the noise-producing mechanisms downstream of that point. Thus, only noise from the higher-frequency sources near the nozzle exit will exhibit the full reductions expected in flight.

It is clear that for adequate aerodynamic simulation the minimum size required for the co-flowing stream depends on the frequency range of interest. In the rear arc of the jet, it is usually acceptable to consider only Strouhal numbers above about 0.1, and from Figure 11 it can be seen that an area ratio of 50 will suffice for this purpose. At around 90° to the jet axis, and into the forward arc, however, a Strouhal number limit of 0.3 is generally adequate and the area ratio required is reduced to 20.

These constraints are the only criteria which need to be considered for measurements at 90° to the jet axis where propagation effects through the secondary shear layer can be neglected. And the adequacy of an area ratio of 20 can be confirmed by the examination of more extensive data for the changes in OASPL. This is demonstrated in Figure 13 which shows the dependence of the relative velocity exponent on area ratio.

Since it is reasonable to assume that the effects of flight are simulated for the OASPLs if the main noise-producing regions of the jet are adequately sheathed, it should be possible from a knowledge of the source distribution of the jet noise to estimate the minimum size of secondary flow that is required. It is known[3,15] that most of the noise emitted laterally from a jet at a typical flight condition ($V_a/V_j = 0.2$) is generated within about 8 diameters of the nozzle exit. A simple calculation (assuming a 7° half-angle for the secondary potential core) shows that an area ratio of about 23 is necessary to sheath this region, and the good agreement of this result with the value derived experimentally provides a convincing demonstration of the validity of the simple model that has been used to explain aerodynamic flight-simulation.

6.2 The influence of shear layer propagation

At angles other than 90° to the jet axis it is necessary, as already mentioned, to correct the noise levels measured by a microphone outside the flight-simulating stream for the effects of the propagation of the sound through the secondary shear layer.

The theories proposed by Amiet[8] and Jacques[1] both approximate the shear layer to an interface of zero thickness (i.e. with a width that is small compared with the wavelength of the incident sound). Amiet considers the shear layer as a plane while Jacques examines both a plane and, more realistically, a cylindrical interface. While Amiet presents equations that allow the measured sound levels to be corrected to what would be measured were the surrounding airstream to extend beyond the microphone, Jacques corrects the measured data to flight conditions. For the plane interface, both theories agree when applied to the same experimental arrangement.

For a cylindrical interface, the theoretical corrections exhibit a frequency dependence; however this may be removed by considering the high frequency limit of the solution and postulating that the waves transmitted from successive reflections at the interface are uncorrelated. Both of these assumptions can be justified[1].

It is worth stressing that the shear layer corrections are independent of the nature of the noise source and only depend on the properties of the surrounding airstream. The theories consider refraction through the shear layer as the dominant mechanism distorting the levels measured in the far field and neglect scattering and sound generation from the turbulent shear layer itself. The effect of the refraction is not only to alter the angle of propagation of the sound but also to affect the rate of decay of its intensity in the ambient medium. Hence it is not possible to allow for the presence of the interface simply by moving the microphone to a different position, as at first sight might appear to be the case.

The effect of these corrections is to increase the noise levels measured in the forward arc (i.e. upstream of the nozzle exit) and to reduce the levels in the rear arc. When sound radiating at 90° to the jet axis crosses the interface, there is no reduction of the sound intensity although there is a small change in the emission angle of the sound due to

its downstream convection in the secondary flow. This effect may normally be neglected for the range of operating conditions encountered in practice, and hence the data at this angle can be used without correction. The theoretical corrections developed by Jacques for a cylindrical interface are described in Appendix B in a form that enables them to be applied conveniently to the measured data.

It is intended now to assess the validity of the corrections by comparing the static-to-flight noise changes measured outside the flight-simulating stream with the results from the tests conducted in the 24 ft wind-tunnel.

Considering first the changes in OASPL, the noise reductions expressed in terms of the relative velocity exponent m are plotted against area ratio in Figure 14 for angles of 30° and 60° to the jet axis - the wind-tunnel data have been extrapolated from 35° to 30°. The noise reductions measured outside the secondary stream at a constant geometric angle are compared with the same data after corrections have been applied for shear layer refraction assuming both a cylindrical and a plane interface. It can be seen that the corrections for a cylindrical interface give generally better agreement with the wind-tunnel data and are adequate for correction provided that the secondary stream is large enough for aerodynamic simulation. But there is a tendency for the theory to over-correct the data at a low angle to the jet axis. In Figure 15, the corrected field shapes at an area ratio of 210 are compared with the levels that are predicted from the wind-tunnel tests. The agreement throughout the rear arc is excellent and there is no reason to suppose that the results would be any worse in the forward arc provided that the analysis is limited to those angles below which the incident sound waves do not undergo total internal reflection at the shear layer.

Work conducted recently at NGTE to simulate the effects of flight on the noise from heated jets and on low-frequency internal noise[16] has indicated that these refraction corrections are liable to become less precise at low angles to the jet axis where the corrections are both large and vary rapidly with angle. This limitation may arise from the sound propagating through an increased thickness of shear layer such that it is no longer approximated adequately by a simple velocity discontinuity.

Before correcting the spectral levels using Jacques' theory, some uncorrected data are shown. In Figures 16 and 17 standardised spectra at various area ratios are compared with the wind-tunnel results for angles of 30° (35° for the wind-tunnel) and 60° to the jet axis. At the lowest area ratios flight is not simulated aerodynamically and the spectra show similar trends to those at 90°, i.e. only giving noise reductions at the higher frequencies. However for an area ratio of 210, where aerodynamic simulation should be complete, the 'flight' spectra still differ noticeably from the wind-tunnel results, and it is this difference which the application of the refraction corrections will be expected to reduce.

After applying refraction corrections, the data available are such that comparisons of static and flight spectra at low angles can be made most conveniently at a sound emission angle of 40°; the spectra from the wind-tunnel tests have been interpolated to give information at this angle. The shear layer correction has been applied using Jacques' theory for a cylindrical interface, and the static and standardised 'flight' spectra are shown in Figure 18. It can be seen that, when the area ratio is sufficient for the aerodynamic simulation of flight, the estimated noise reductions have a frequency dependence similar to those of the wind-tunnel results, despite some differences in the shape of the static spectra obtained from the two test facilities. Bearing in mind that the refraction corrections do not contain frequency-dependent terms, at first sight it appears to be strange that the spectral shape should change after correction. This anomaly arises because the flight spectrum, which is only altered in magnitude by refraction, is now being compared with the static spectrum at the same emission angle rather than the same geometric angle.

The overall position regarding the criteria for the adequate simulation of flight effects can be summarised as follows. In the rear arc, where Strouhal numbers less than 0.1 need not usually be considered, an area ratio of 50 has been shown to be sufficient except at low angles where the refraction corrections become large and vary rapidly with angle. This conclusion remains valid at 90° to the jet axis and should be applicable in the forward arc (except at extreme angles where total internal reflection can occur). If, however, the low-frequency limit can be raised to a Strouhal number of 0.3, as for example when jet noise data at the higher angles are of primary interest, the area ratio required can be reduced to 20.

7.0 The simulation of flight for heated jets

While the foregoing analysis is based on data derived from unheated subsonic jets, it should for practical purposes be equally applicable to heated subsonic jets.

Tests have recently been conducted in the Noise Test Facility (NTF) at NGTE to study the effects of flight for a conical nozzle and a 6-chute silencer nozzle supplied with heated air. A secondary flow with an area ratio of 25 was used which should be adequate to simulate flight down to a Strouhal number of about 0.2 for the conical nozzle. The same area ratio used with the 6-chute nozzle would be expected to provide data at lower frequencies because of the shorter mixing length. Data are also available for similar nozzles tested in the 24 ft wind-tunnel. Both sets of data are substantially free of rig and other extraneous noise sources.

A comparison is made of static-to-flight results in the rear arc which are typical of each nozzle. The static and flight spectra at the standardised conditions are plotted in Figure 19 for a sound emission angle of 37°. Although there are some differences between the static spectra measured in the two facilities, the good agreement between the two sets of data provides additional evidence that comparatively small secondary streams can be used to study the effects of flight provided that refraction corrections are applied.

8.0 Concluding remarks

It has been shown in this Report that it is possible to simulate the effects of flight on jet noise using a comparatively small secondary air-stream and with the microphone positioned outside the flow. Corrections for the propagation of the noise from the test jet through the shear layer of the secondary flow are necessary but it has been shown that an existing theory is adequate for this purpose. The studies have been restricted to the consideration of the noise from conical nozzles with a subsonic jet flow. Because the underlying mechanisms are reasonably well understood, it is possible with some knowledge of the aerodynamic structure of the jet flow, to apply the results to studies of the mixing noise from other nozzle designs.

The minimum area of the flight-simulating stream is limited by the necessity for flight to be simulated aerodynamically in the main noise-producing regions of the source. It is shown that a secondary-to-primary

area ratio of about 50 is sufficient for this for Strouhal numbers greater than 0.1. In many circumstances, however, a minimum frequency corresponding to a Strouhal number of 0.3 is adequate and in such cases the required area ratio can be reduced to 20. The area ratios quoted here are based, not on the area of the secondary nozzle, but on the area of the potential core of the secondary flow in the plane of the primary nozzle exit.

APPENDIX A

List of symbols

General Notation

a_o	ambient velocity of sound (m/s)
A_j	primary nozzle area (m^2)
d	primary nozzle diameter (m)
D	secondary nozzle diameter (m)
f	frequency (Hz)
h	radius of secondary nozzle (m)
k	relative velocity exponent (defined in expression 4)
m	relative jet velocity exponent (defined in expression 1)
Ma	Mach number of the secondary stream
n	jet velocity exponent (defined in expression 1)
R	distance from the primary nozzle exit to the microphone (m)
St	jet Strouhal number, ($f \times d/V_j$)
T_j	jet total temperature (K)
V_a	secondary stream velocity (m/s)
V_j	primary jet velocity (m/s)
V_{rel}	relative primary jet velocity, $V_j - V_a$ (m/s)
θ_m	geometric angle of the microphone relative to the jet axis
$\bar{\theta}$	angle of emission of the sound from the source, relative to the jet axis
θ'	direction of propagation of the sound through the secondary stream, relative to the jet axis
$(\rho_j/\rho_{isa})^{\omega}$	jet density correction[9]
$\Delta OASPL_{\theta}$	reduction in overall sound pressure level at an angle $\bar{\theta}$ to the jet axis upon the introduction of secondary flow

General Notation (cont'd)

$\Delta SPL_{\theta,f}$	reduction in $\frac{1}{3}$-octave sound pressure level (centred on frequency f) upon the introduction of secondary flow, at an angle $\bar{\theta}$ to the jet axis
$\Delta OASPL'_{\theta}$	modified reduction in OASPL upon the introduction of secondary flow
$\Delta SPL'_{\theta,f}$	modified reduction in $\frac{1}{3}$-octave SPL upon the introduction of secondary flow

Additional Notation used in Appendix B

R_1 , R_2	radii of curvature of the wave fronts after propagation through the shear layer (m)
r	distance travelled by the wave in the ambient air (m)
$\bar{r}$	distance travelled by the wave fronts in the flight-simulating stream measured relative to the airflow; h cosec $\bar{\theta}$ (m)
θ	angle of propagation of the sound in the ambient air relative to the jet axis
$\bar{\theta}_{\ell}$	limiting sound emission angle for total internal reflection at the secondary shear layer
ΔdB_{POLAR}	shear layer correction to 'flight' noise level; polar microphone traverse
ΔdB_{LIN}	shear layer correction to 'flight' noise level; linear traverse
β	$1 + Ma \cos \bar{\theta}$
δ	astigmatism correction to the noise level for a cylindrical interface
$10 \log_{10} C$	wave curvature correction to the noise level for a cylindrical interface

APPENDIX B

Corrections for the effects of shear layer refraction

It is intended in this Section to outline briefly the corrections that are required to data measured outside the flight-simulating stream to allow for the propagation of the sound through the secondary shear layer. The corrections derived by Jacques (assuming the shear layer to be approximated by a cylindrical interface) are expressed in a form that enables them to be applied with ease to noise data measured using either a linear or a polar microphone traverse.

Corrections are required to the 'flight' data to allow for the changes in both the intensity and propagation angle of the sound brought about by its refraction through the shear layer. These angle and level corrections are described separately with the aid of the diagram given in Figure 20.

a. The angle correction

The emission angle, $\bar{\theta}$, of the sound that is received at a microphone positioned at a geometrical angle θ_m and at a distance R from a noise source is given by

$$\frac{\cos\bar{\theta}}{\left[(1 + Ma\cos\bar{\theta})^2 - \cos^2\bar{\theta}\right]^{\frac{1}{2}}} = \frac{\left(\frac{R}{h}\right)\cos\theta_m - \frac{\cos\bar{\theta} + Ma}{\sin\bar{\theta}}}{\left(\frac{R}{h}\right)\sin\theta_m - 1} \qquad \text{....(A1)}$$

This equation enables the microphone to be repositioned with increasing 'flight' speed so that it receives sound emitted from the source at a constant angle. This is clearly an attractive experimental technique since it allows static and flight data to be compared at constant sound emission angles without need for angular interpolation. However, this approach would only be practical when the position of the microphones can be easily altered with increasing secondary velocity.

Alternatively, the position of the microphone can be fixed (as for the data analysed in this Report) and the emission angle of the sound calculated subsequently for each 'flight' speed.

If the measurements are taken on a linear traverse, it is necessary to calculate this correction for the appropriate value of R at each angle.

The solution of Equation (A1) is limited in the forward arc to angles less than $\bar{\theta}_\ell$ where

$$\cos \bar{\theta}_\ell = -\frac{1}{1 + Ma} \qquad \ldots.(A2)$$

This corresponds physically to the sound emission angle at which the incident waves start to undergo total internal reflection, rather than refraction, at the shear layer. It is not possible to obtain information on the effects of flight at higher angles to the jet axis from a microphone positioned outside the flight-simulating stream.

b. The level correction

The refraction of the sound at the secondary shear layer may be considered to have two effects on the noise levels measured in the ambient air. Firstly, the sound levels are altered because of the change in the solid angle of the incident ray bundles as a result of their propagation through the shear layer. This correction is described by Jacques as arising from wave curvature effects. Secondly, there is a distance correction to allow for the fact that the apparent distance of the source from the interface varies with the observation angle. This effect is caused by astigmatism and vanishes if the microphone is positioned an infinite distance from the interface.

For data taken on a polar traverse, the noise level measured outside the airstream on a microphone positioned at an angle θ_m to the jet axis should be increased by

$$\Delta dB_{POLAR} = 10 \log_{10} C + \delta \qquad \ldots.(A3)$$

before it is compared with the static data emitted at the same sound emission angle (i.e. measured on a microphone positioned at angle $\bar{\theta}$ to the jet axis).

The wave curvature effect is given by

$$10 \log_{10} C = 10 \log_{10} \left\{ \frac{\left[\beta^2 \sin \bar{\theta} + (\beta^2 - \cos^2 \bar{\theta})^{\frac{1}{2}}\right]^2}{4 \beta^6 \sin \bar{\theta} (\beta^2 - \cos^2 \bar{\theta})^{\frac{1}{2}}} \right\} \quad \text{....(A4)}$$

and the astigmatism correction by

$$\delta = 10 \log_{10} \left\{ \left(\frac{r}{R}\right)^2 \left(1 + \frac{R_1}{\bar{r}} \frac{\bar{r}}{r}\right) \left(1 + \frac{R_2}{\bar{r}} \frac{\bar{r}}{r}\right) \right\} \quad \text{....(A5)}$$

where $\beta = (1 + Ma \cos \bar{\theta})$,

$$\frac{R_1}{\bar{r}} = \frac{\beta (\beta^2 - \cos^2 \bar{\theta})}{\sin^2 \bar{\theta}}, \quad \text{....(A6)}$$

$$\frac{R_2}{\bar{r}} = \frac{\beta \sin \bar{\theta}}{(\beta^2 - \cos^2 \bar{\theta})^{\frac{1}{2}}}, \quad \text{....(A7)}$$

$$\frac{r}{R} = \left\{ \left(\sin \theta_m - \frac{h}{r}\right)^2 + \left[\cos \theta_m - \frac{h}{R}\left(\frac{\cos \bar{\theta} + Ma}{\sin \bar{\theta}}\right)\right]^2 \right\}^{\frac{1}{2}},$$

....(A8)

and $$\frac{\bar{r}}{r} = \left(\frac{h}{R}\right)\left(\frac{R}{r}\right)\frac{1}{\sin \bar{\theta}}. \quad \text{....(A8)}$$

The level corrections for a microphone traversed on a polar arc about the primary noise source may be calculated from Equations (A3) to (A8) using the following data:

θ_m, the geometric angle of the microphone to the jet axis

Ma, the Mach number of the flight-simulating stream

h, the radius of the secondary nozzle

R, the radius of the polar microphone traverse.

When the noise measurements are taken other than by traversing the microphone in a polar arc about the primary noise source, it is necessary to modify the level corrections for inverse square law effects.

The correction to the flight data measured on a linear traverse is given by

$$\Delta dB_{LIN} = \Delta dB_{POLAR} + 20 \log_{10} \left(\frac{\sin \bar{\theta}}{\sin \theta_m} \right) \qquad \text{....(A9)}$$

REFERENCES

No.	Author(s)	Title, etc.
1	J. R. Jacques	The noise from the moving aircraft: some relevant models PhD Thesis; Cambridge University Engineering Department August 1975
2	B. J. Cocking W. D. Bryce	An investigation of the noise of cold air jets under simulated flight conditions NGTE Report No. R334 September 1974
3	B. J. Cocking W. D. Bryce	Subsonic jet noise in flight based on some recent wind-tunnel results AIAA Paper No. 75-462 March 1975
4	B. J. Cocking	The effect of flight on subsonic jet noise AIAA Paper No. 76-555 July 1976
5	U. von Glahn D. Groesbeck J. Goodykoontz	Velocity decay and acoustic characteristics of various nozzle geometries in forward flight AIAA Paper No. 73-629 July 1973
6	A. B. Packman K. W. Ng R. W. Paterson	Effect of simulated forward flight on subsonic jet exhaust noise AIAA Paper No. 75-869 June 1975
7	D. H. Reed	Effect of forward velocity on the noise characteristics of dual-flow jet nozzles ASME publication for presentation at the Winter Annual Meeting. New York, NY November 1974
8	R. K. Amiet	Correction of open jet wind-tunnel measurements for shear layer refraction AIAA Paper No. 75-532 March 1975
9	-	Proposed revision to ARP 876 Jet exhaust noise prediction 2nd Draft September 1974
10	Elizabeth M. Francis	Unpublished MOD material

REFERENCES (cont'd)

No.	Author(s)	Title, etc.
11	M. J. Lighthill	On sound generated aerodynamically Part 1 - General theory Proc. Roy. Soc. A211, p.564, 1952
12	J. E. Ffowcs Williams	The noise from turbulence convected at high speed Phil. Trans. Roy. Soc. Vol. 255, No. 1061, p.469, April 1963
13	B. J. Cocking	An experimental study of coaxial jet noise NGTE Report No. R.333 May 1976
14	W. Olsen R. Friedman	Jet noise from coaxial nozzles over a wide range of geometries and flow parameters AIAA Paper No. 74-93 January 1974
15	F. R. Grosche	Distribution of sound source intensities in subsonic and supersonic jets AGARD CP131 1973
16	R. A. Pinker W. D. Bryce	The radiation of plane-wave duct noise from a jet exhaust, statically and in flight AIAA Paper No. 76-581 July 1976

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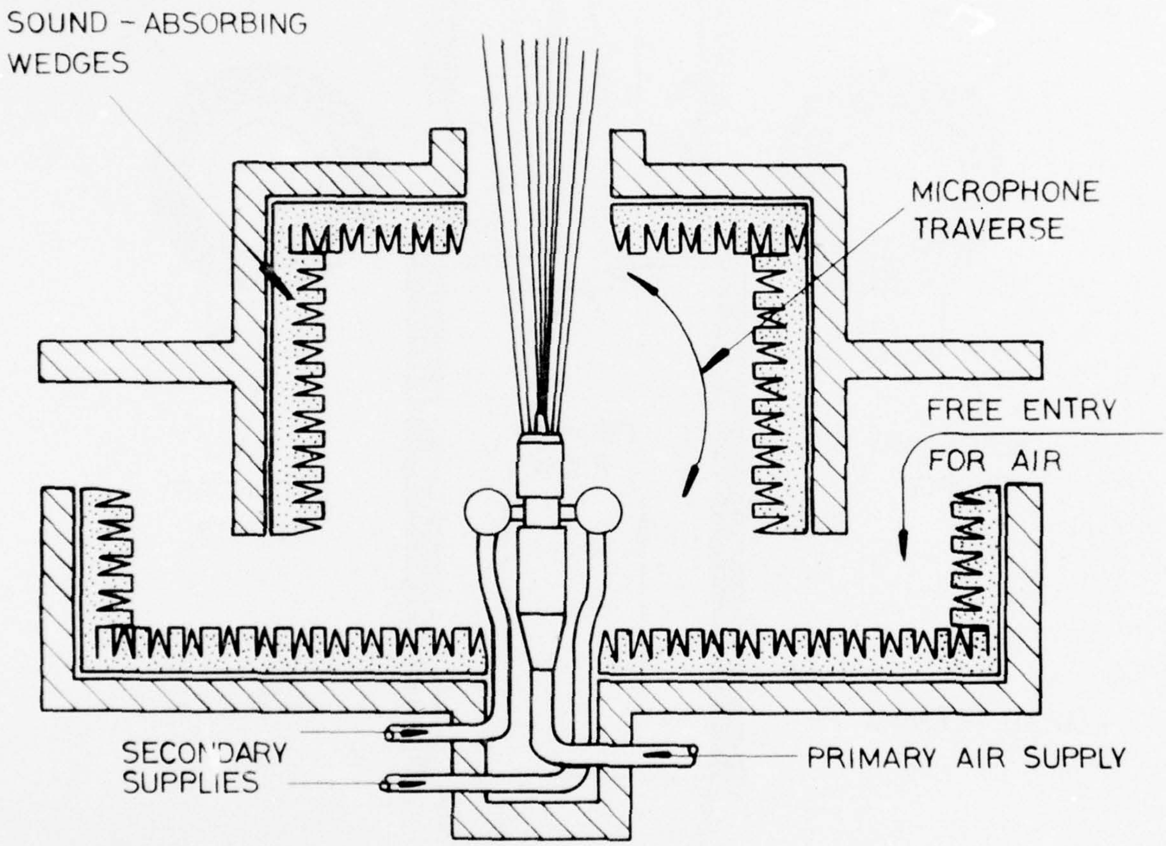


FIG. 1 THE ANECHOIC CHAMBER

SK 121014

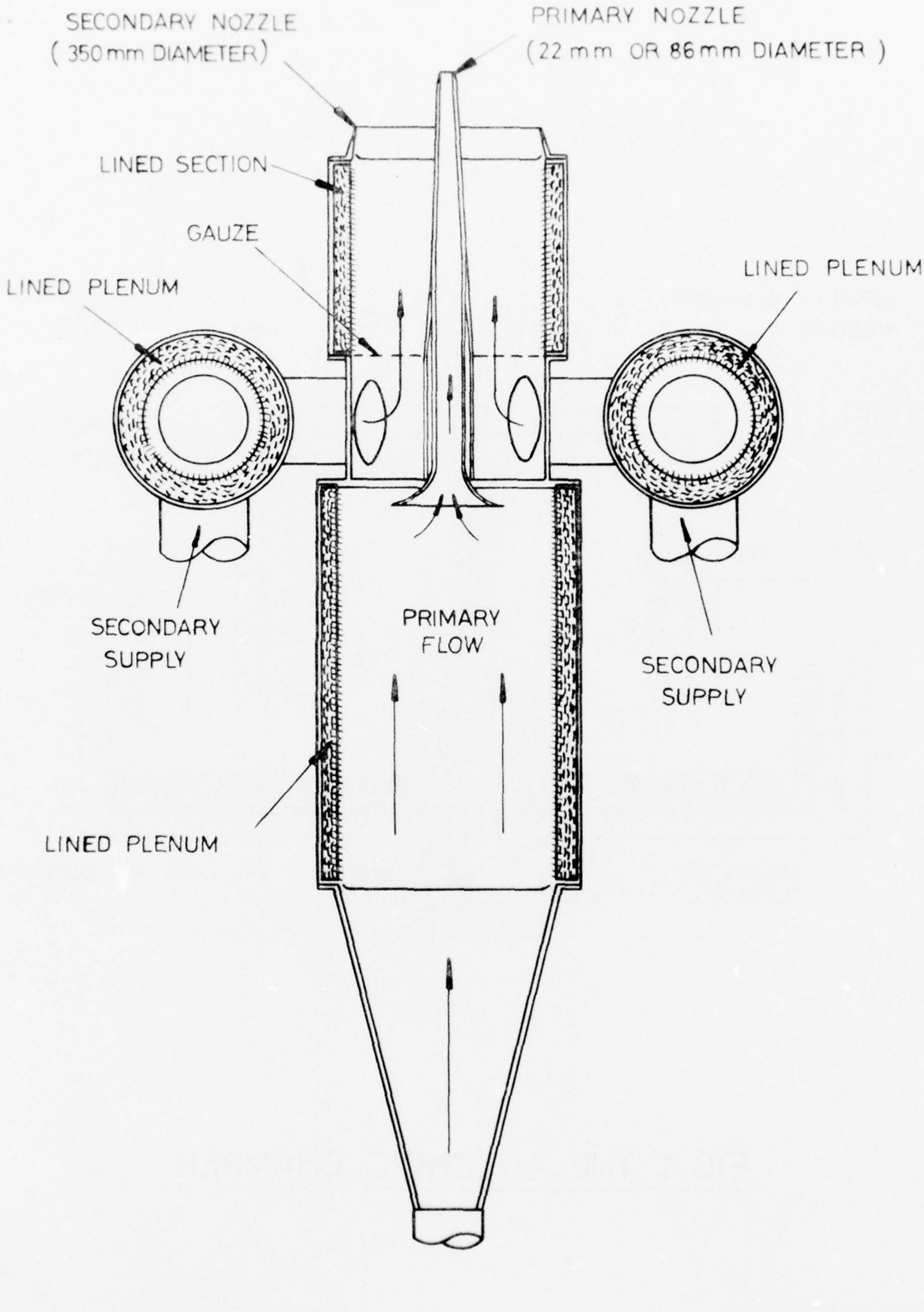


FIG.2 CROSS-SECTION OF THE FLIGHT SIMULATION RIG

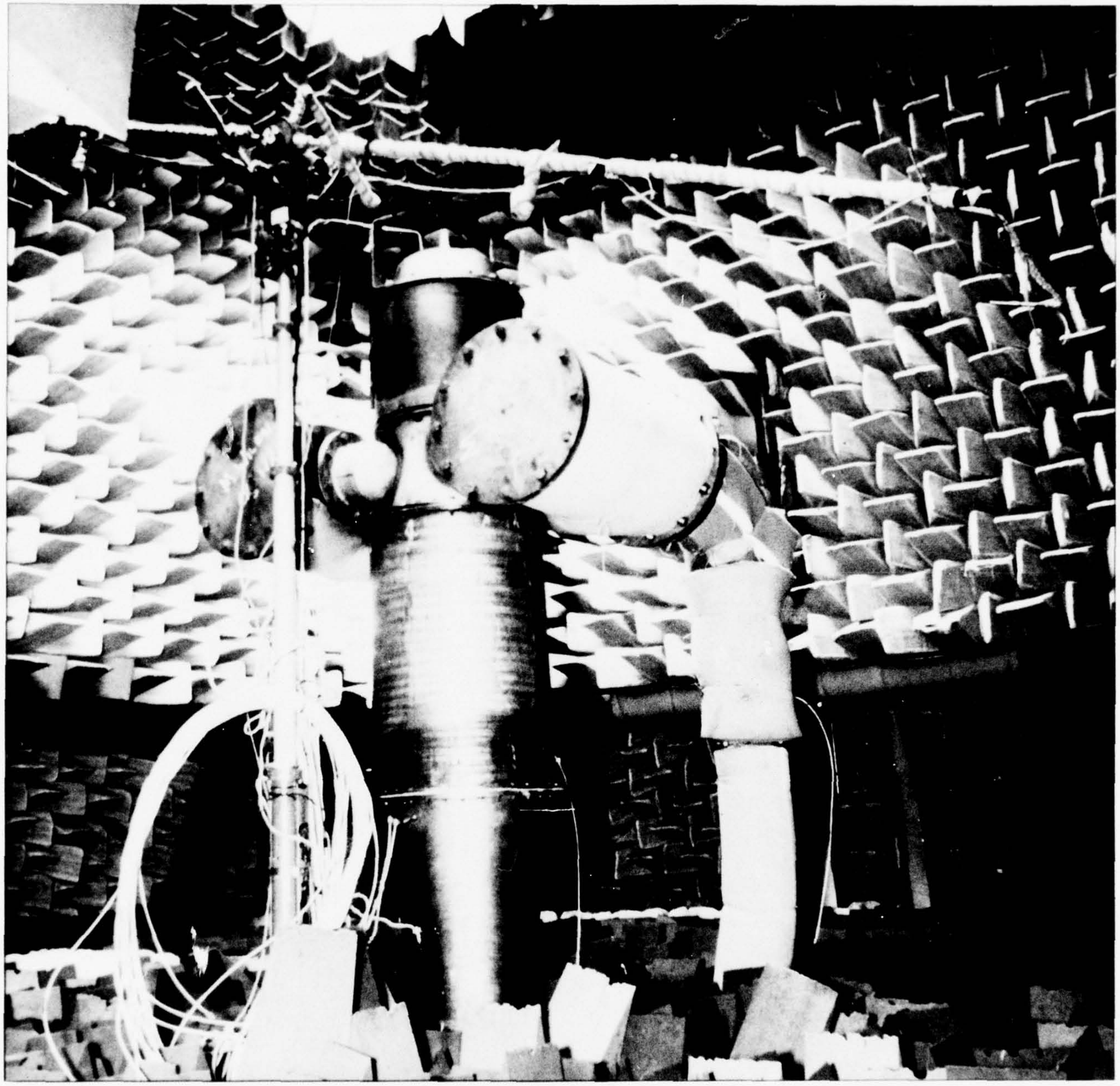
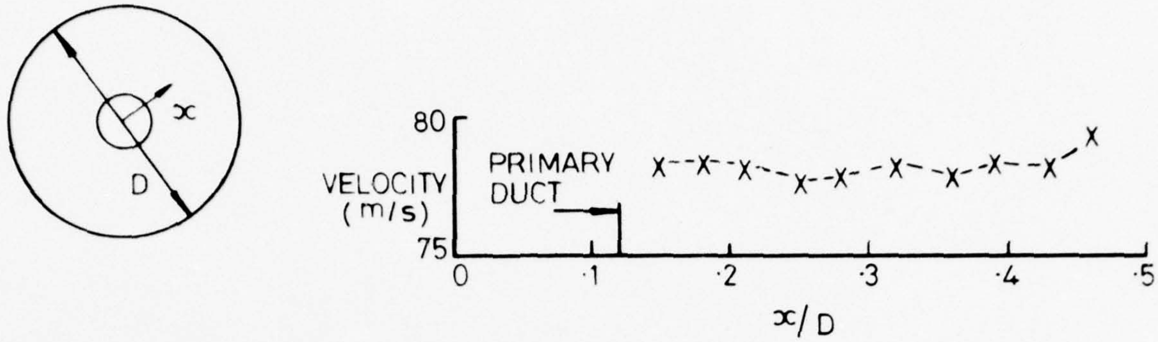
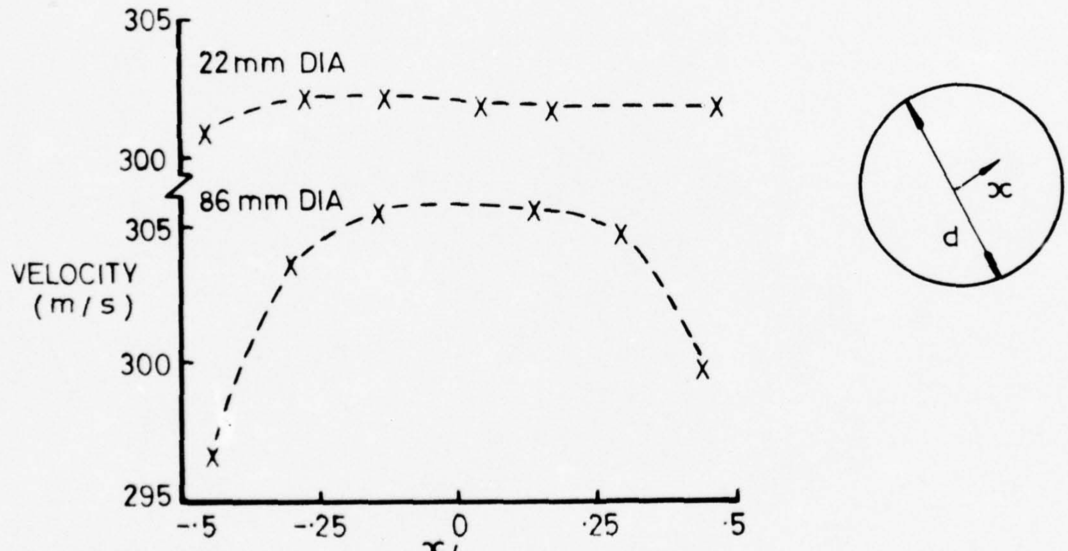


FIG.3 INSTALLATION OF THE RIG IN THE ANECHOIC CHAMBER

SK 121015



a) SECONDARY NOZZLE



b) PRIMARY NOZZLE

FIG.4 TYPICAL VELOCITY DISTRIBUTIONS AT THE NOZZLE EXIT PLANES

121016

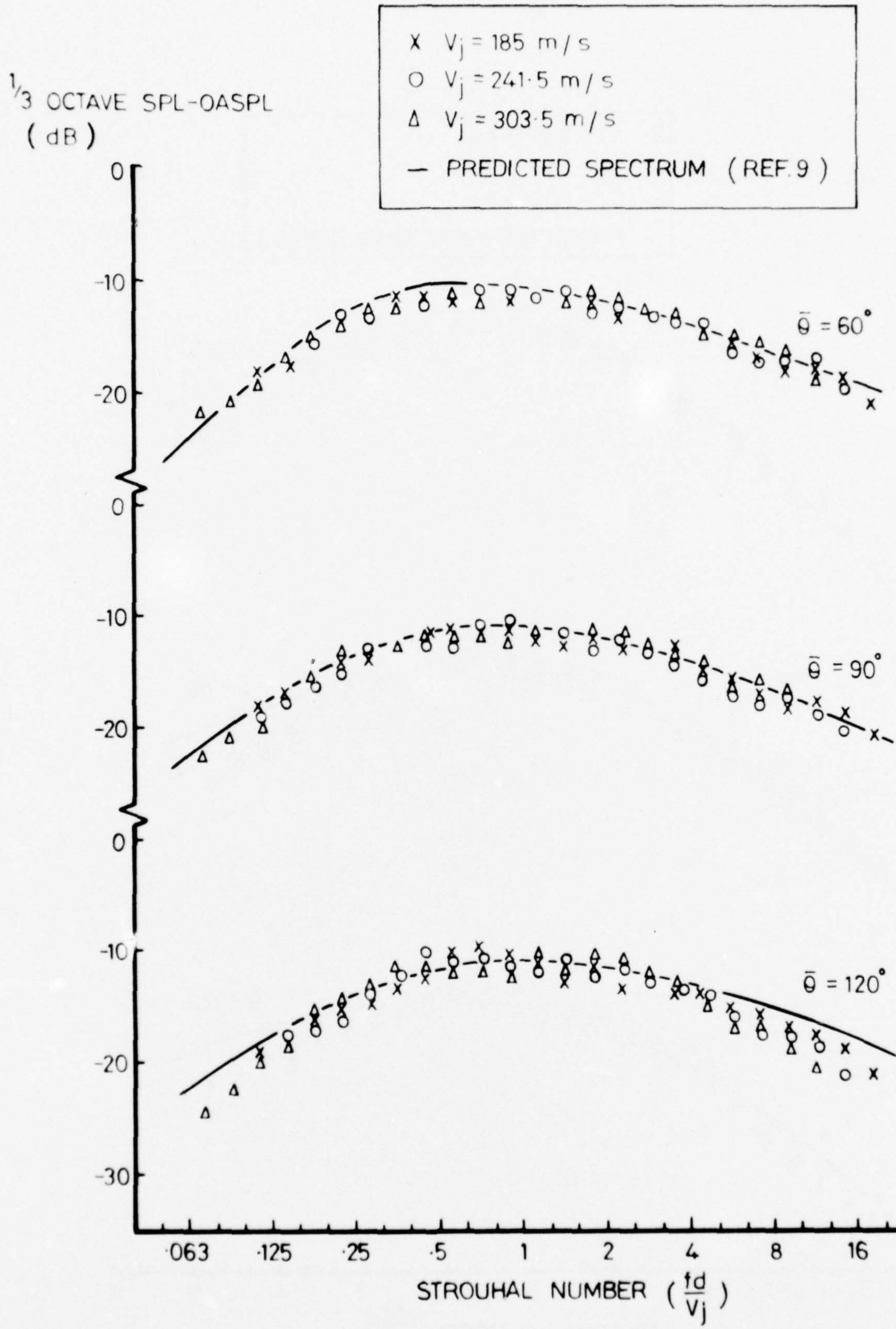


FIG. 5 STATIC RELATIVE SPECTRA FOR THE 86mm DIAMETER NOZZLE

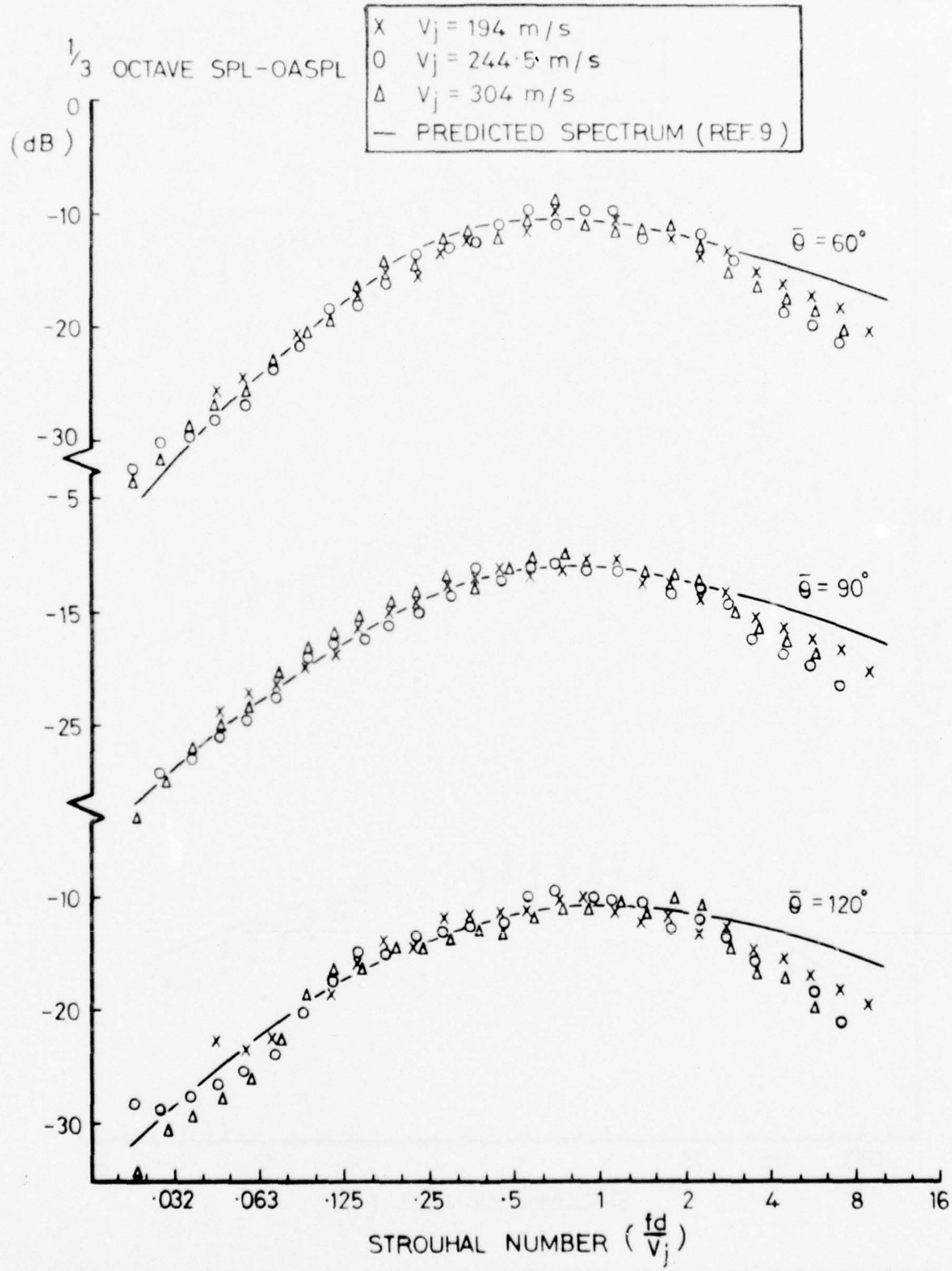


FIG.6 STATIC RELATIVE SPECTRA FOR THE 22 mm DIAMETER NOZZLE

121018

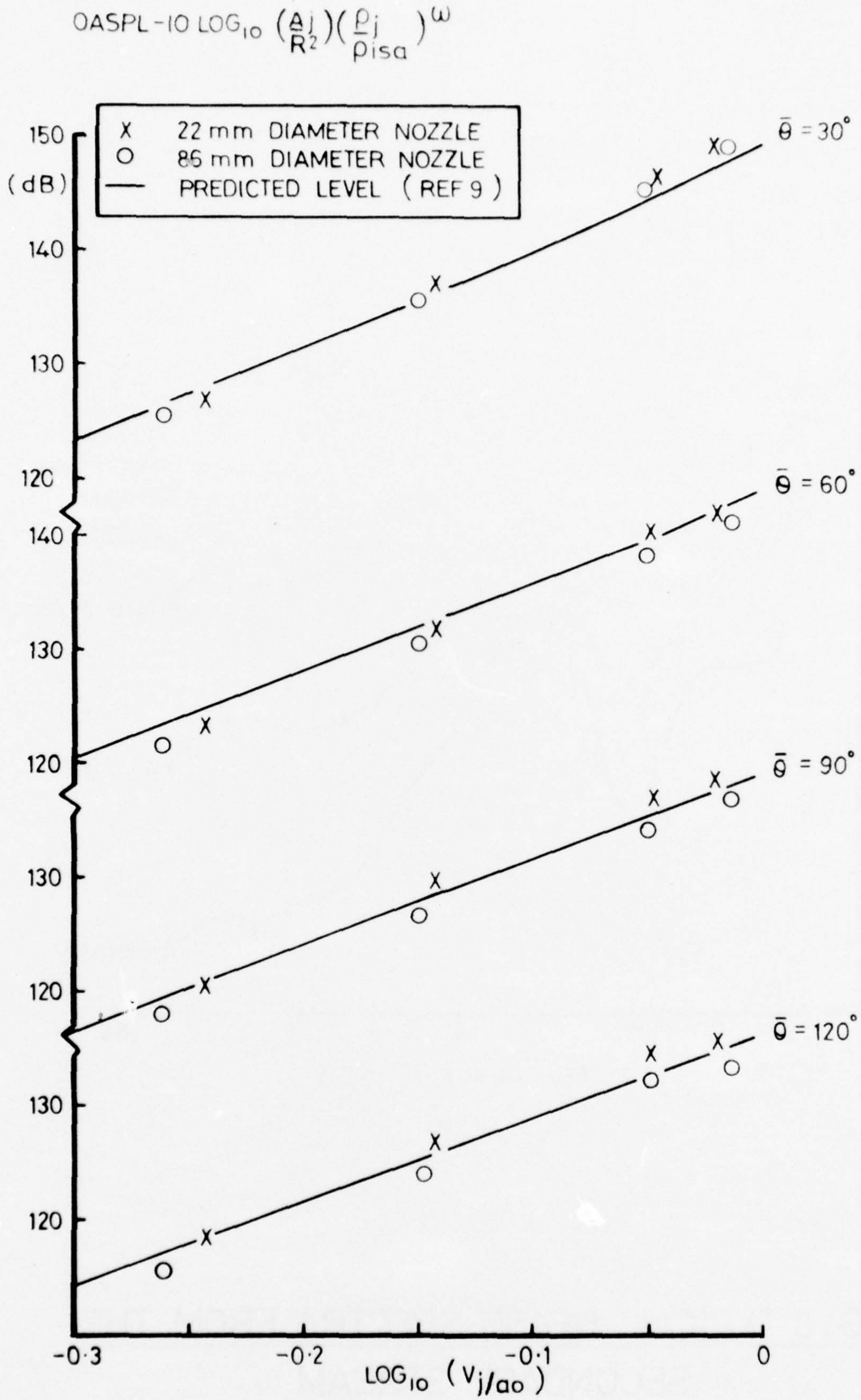


FIG. 7 A COMPARISON OF THE NORMALISED STATIC OASPLS WITH PREDICTION

SK 121019

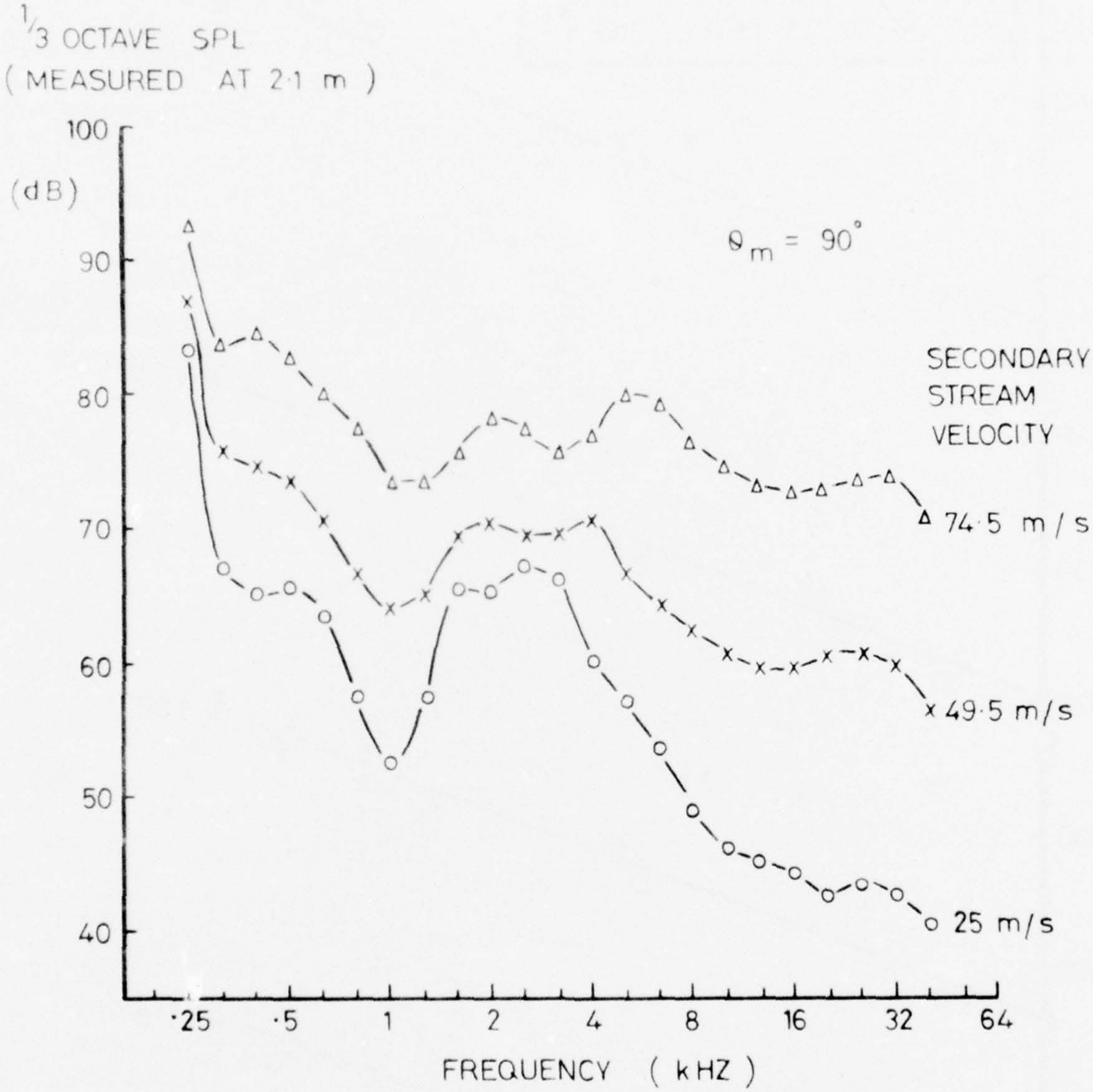


FIG. 8 TYPICAL NOISE SPECTRA FROM THE SECONDARY STREAM

121020

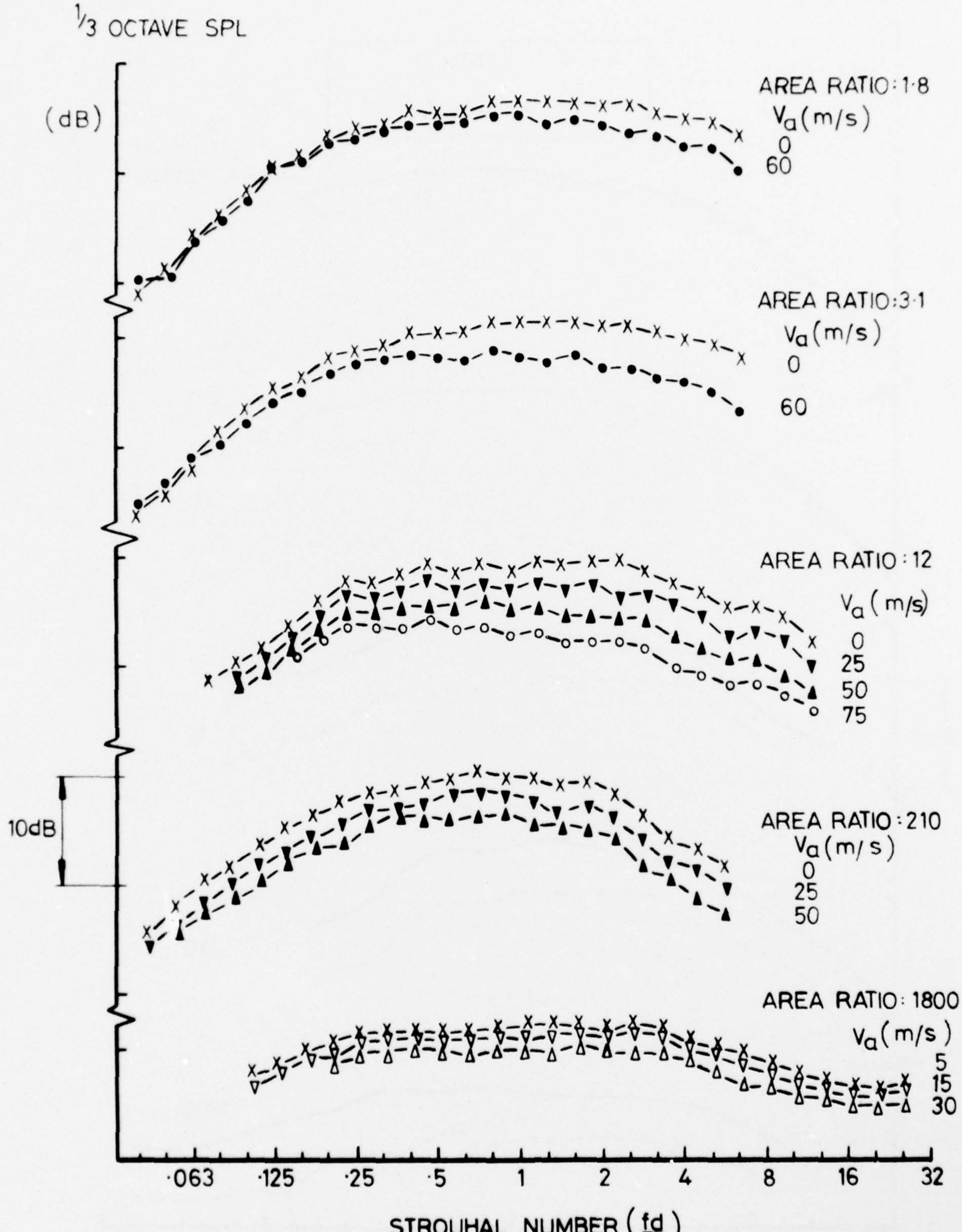


FIG. 9 MEASURED JET NOISE SPECTRA; V_j = 305 m/s, $\bar{\Theta}$ = 90°

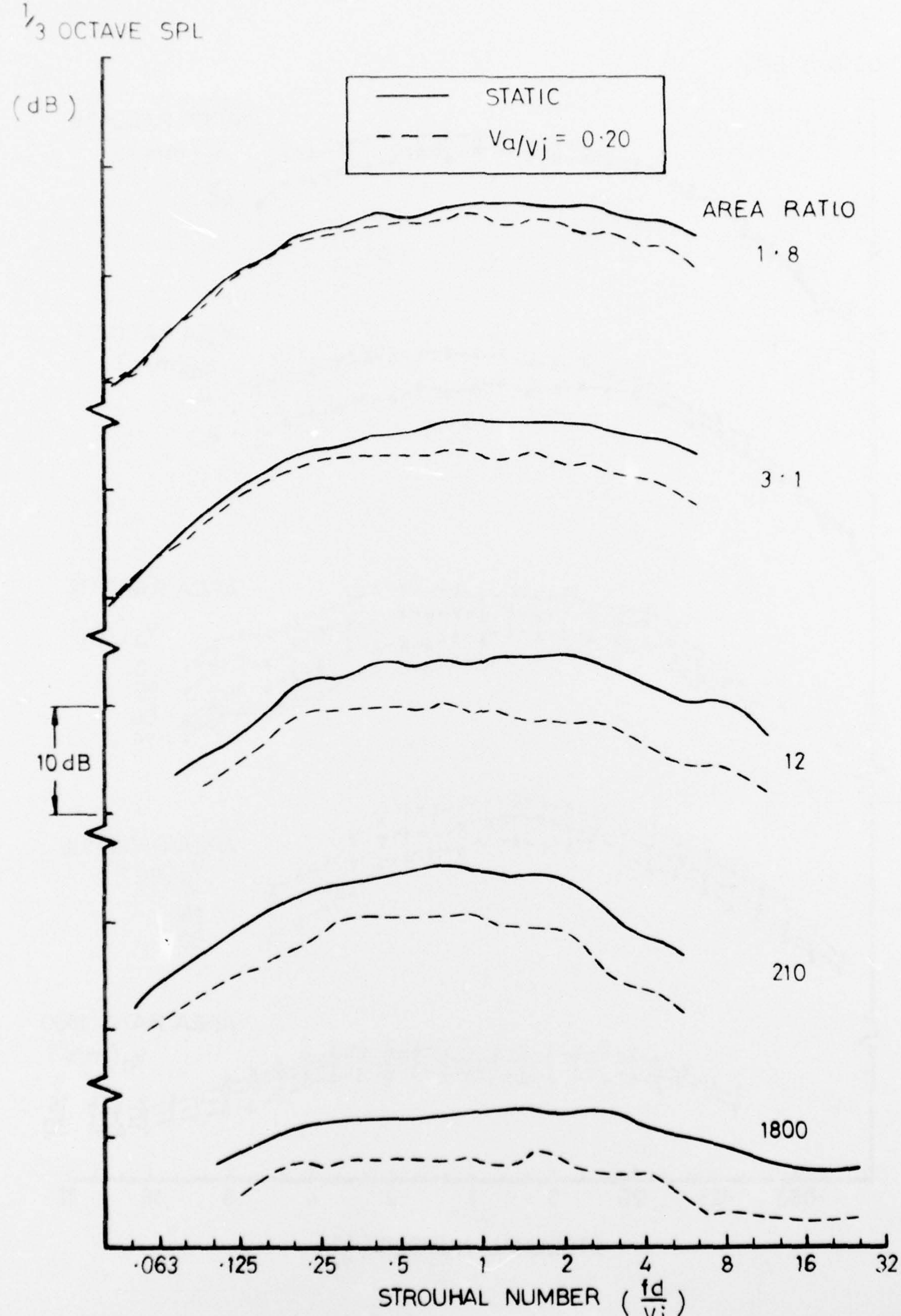


FIG.10 STANDARDISED JET NOISE SPECTRA; $V_j = 305$ m/s, $\bar{\Theta} = 90°$

121022

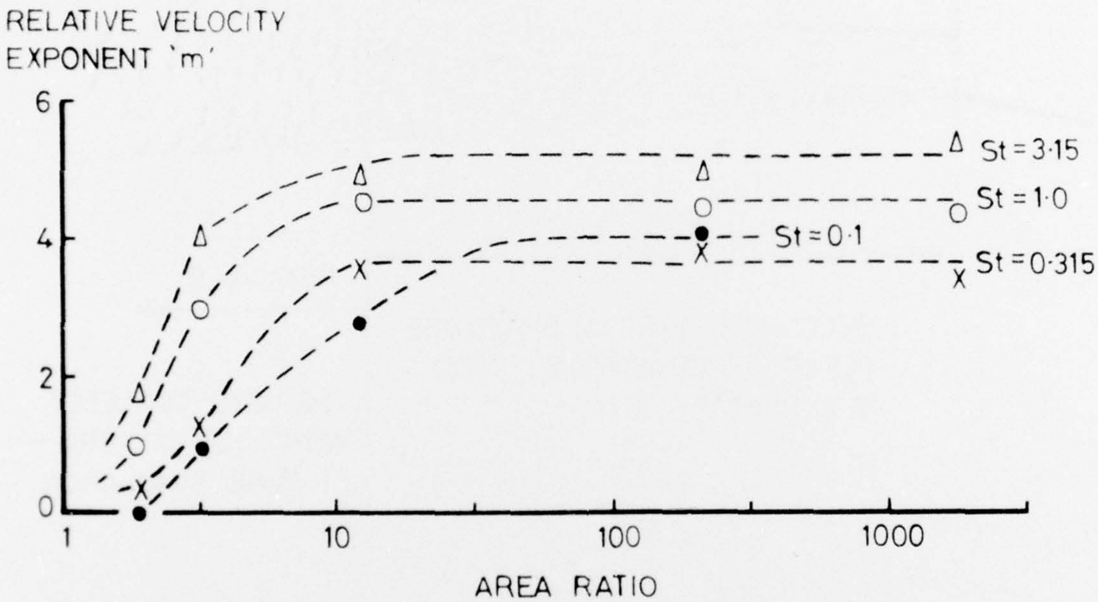


FIG.11 THE VARIATION OF VELOCITY EXPONENT WITH AREA RATIO AT VARIOUS STROUHAL NUMBERS, $\bar{\Theta} = 90°$

SK 121023

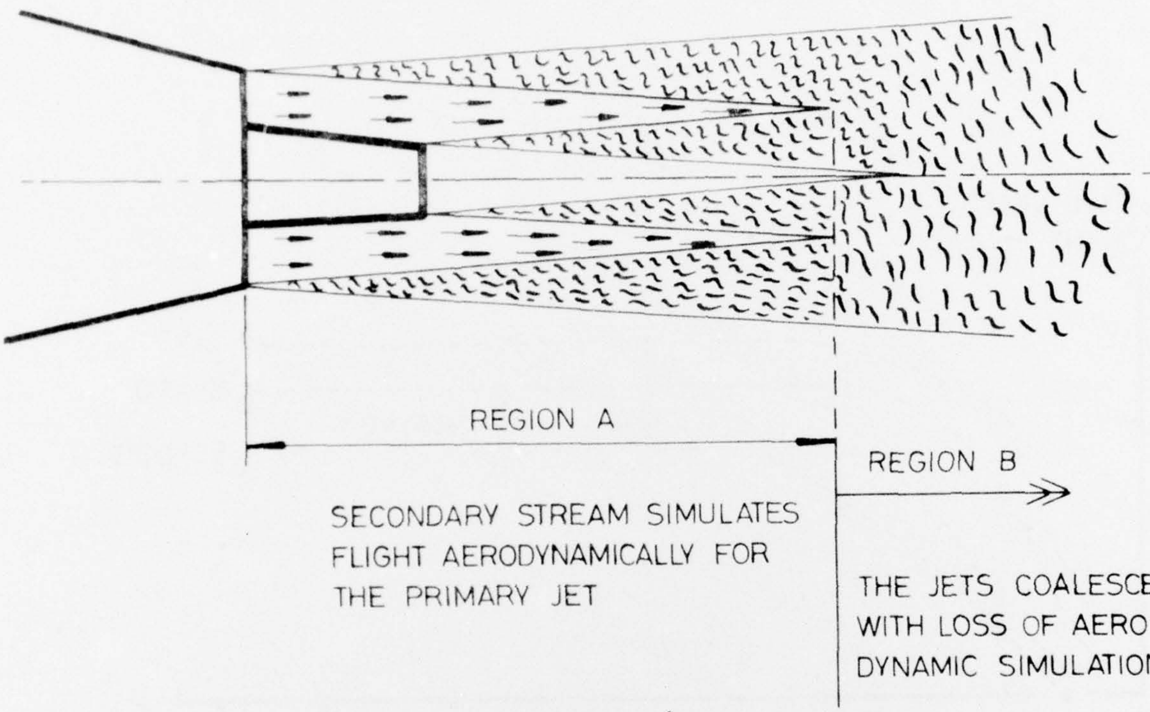


FIG. 12 A SIMPLIFIED VIEW OF THE AERODYNAMIC SIMULATION OF FLIGHT

121024

KEY	
O	NGTE DATA
X	DATA FROM REFERENCE 14

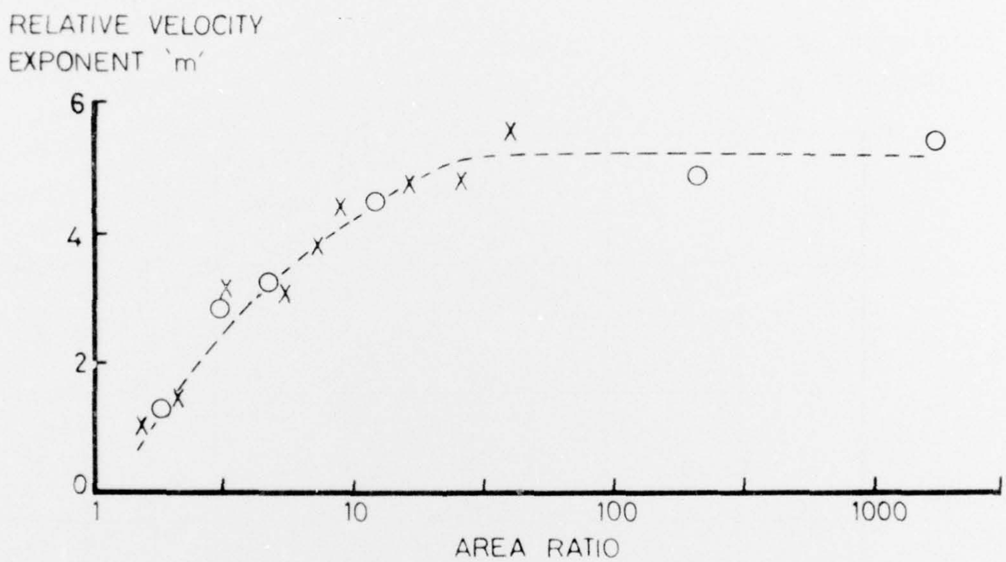


FIG.13 THE VARIATION OF OASPL VELOCITY EXPONENT WITH AREA RATIO; $\bar{\theta} = 90°$

SK 121025

SYMBOL	TYPE OF DATA
○	NO SHEAR LAYER CORRECTIONS
X	CORRECTED ASSUMING CYLINDRICAL INTERFACE
+	CORRECTED ASSUMING PLANE INTERFACE
●	PREDICTED FROM WIND TUNNEL RESULTS (REF. 4)

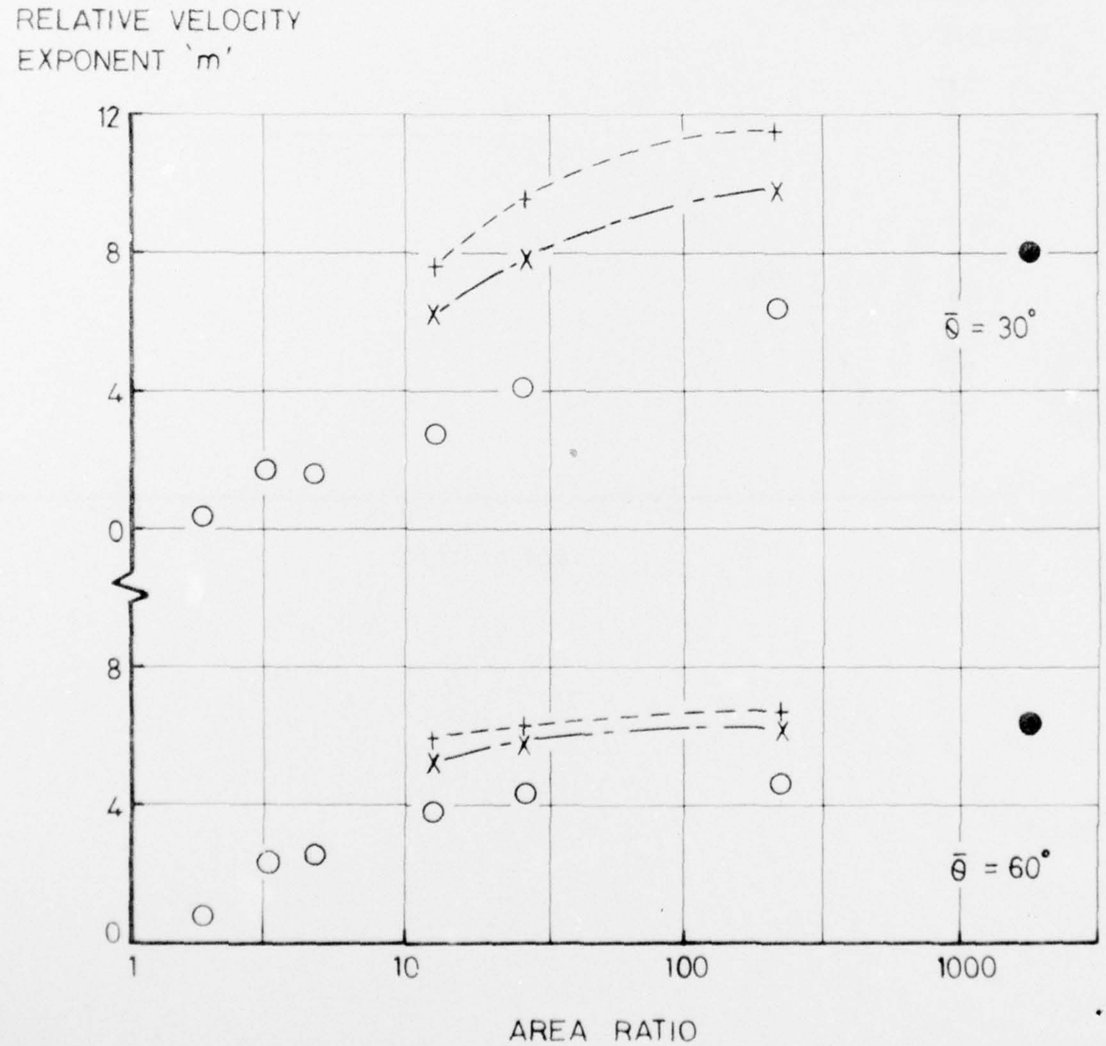


FIG.14 CORRECTION OF THE OASPL VELOCITY EXPONENTS ;

$\bar{\theta}$ = 30° & 60°

KEY	
—O—	MEASURED STATIC OASPLS
- - - -	PREDICTED FLIGHT LEVELS FROM WIND TUNNEL (REF. 4)
X	V_a = 25 m/s } MEASURED 'FLIGHT' LEVELS CORRECTED FOR SHEAR LAYER EFFECTS
+	V_a = 50 m/s } MEASURED 'FLIGHT' LEVELS CORRECTED FOR SHEAR LAYER EFFECTS

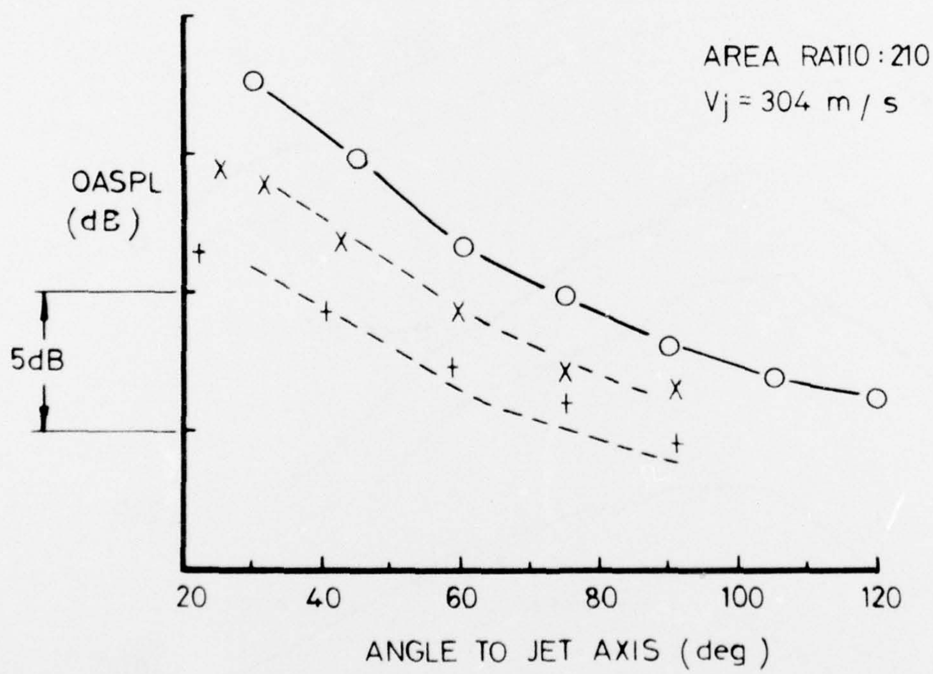


FIG. 15 A COMPARISON OF CORRECTED OASPL FIELD SHAPES WITH PREDICTION.

SK 121027

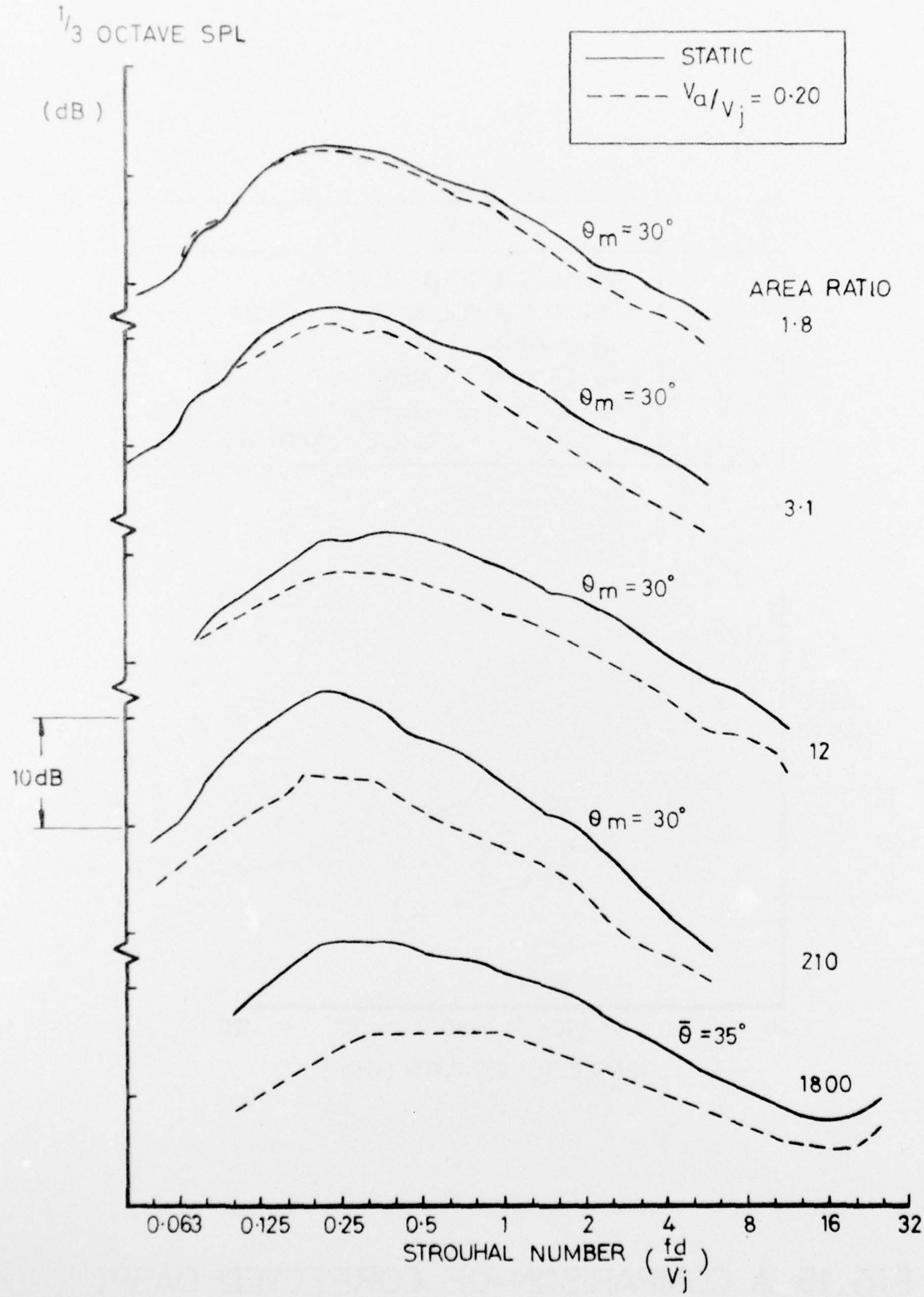


FIG.16 STANDARDISED JET NOISE SPECTRA;

$V_j = 305$ m/s, $\theta_m \sim 30°$

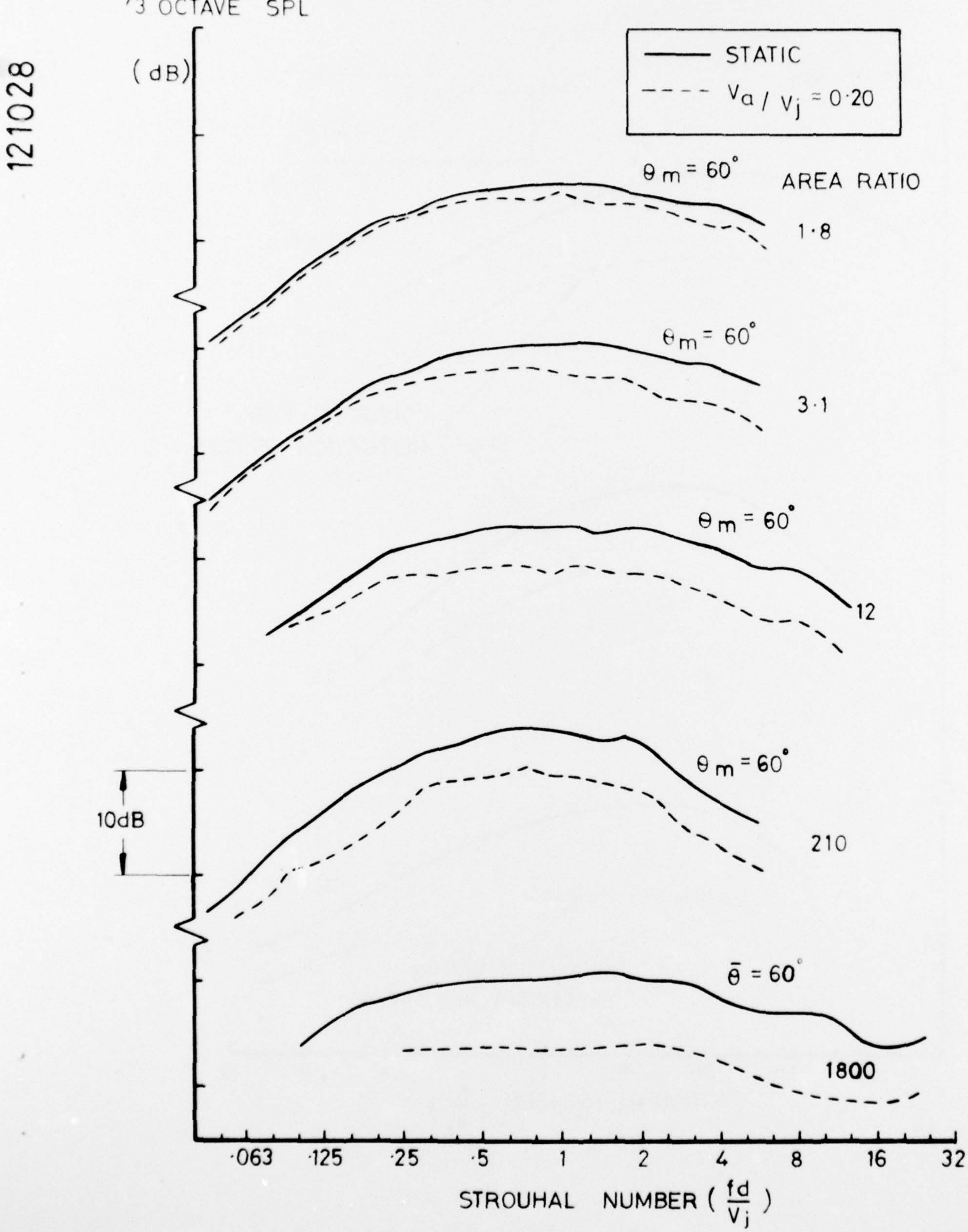


FIG.17 STANDARDISED JET NOISE SPECTRA,

V_j =305 m/s, $\theta m \sim 60°$

SK 121029

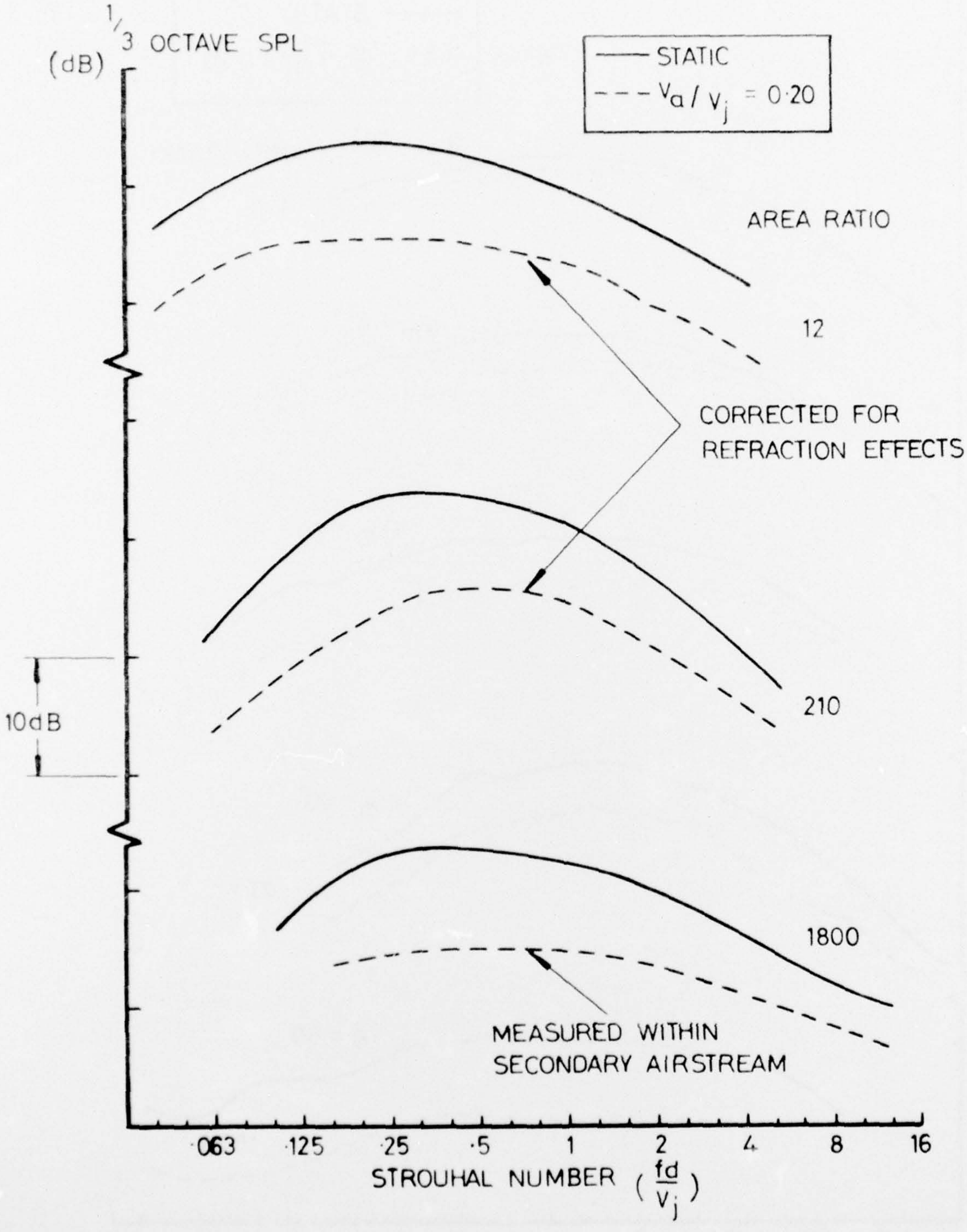


FIG.18 STANDARDISED JET NOISE SPECTRA;

$V_j = 305\ m/s, \bar{\theta} = 40^{\circ}$

121030

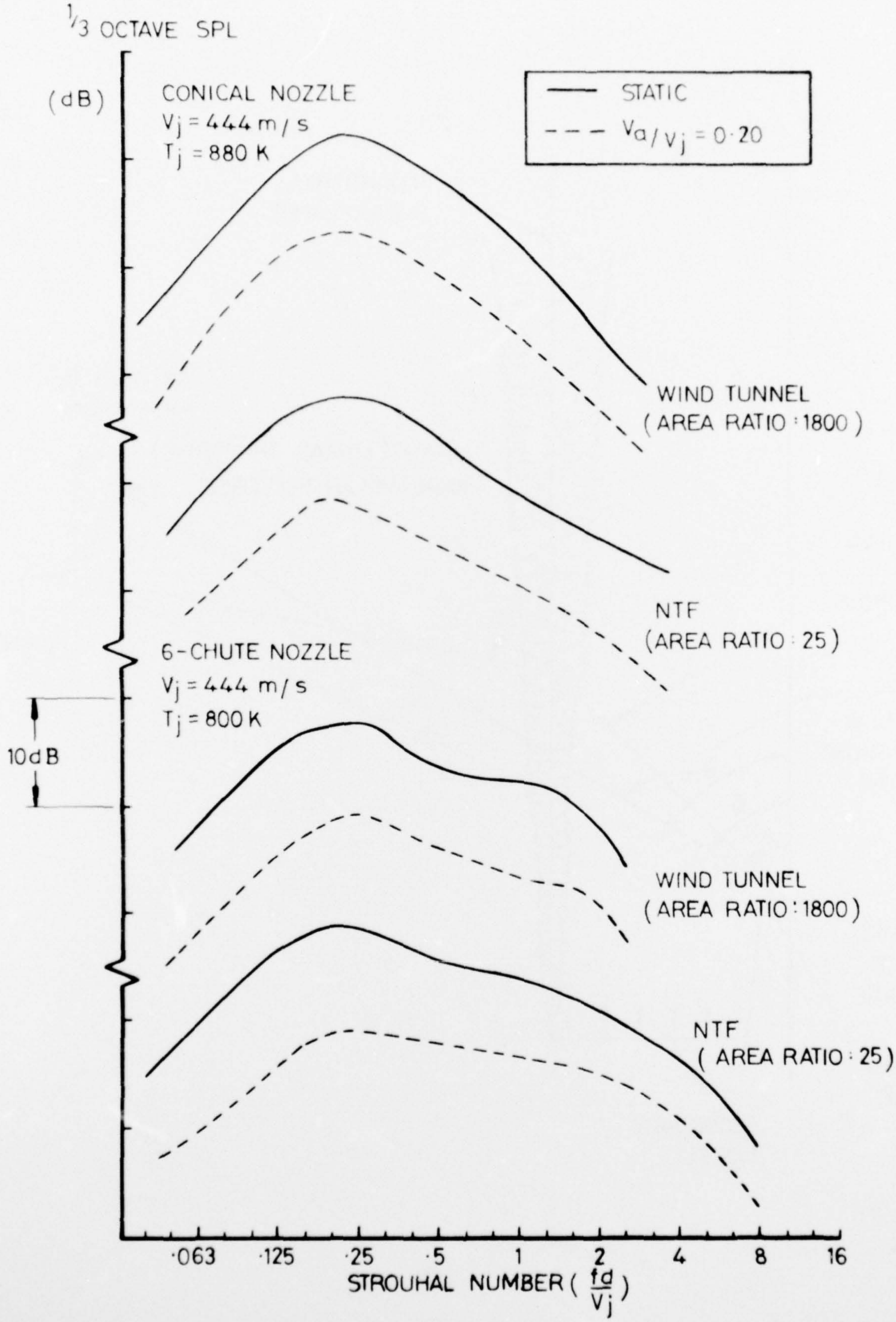


FIG.19 STANDARDISED SPECTRA FROM HEATED JETS, $\bar{\theta}=37°$

SK 121031

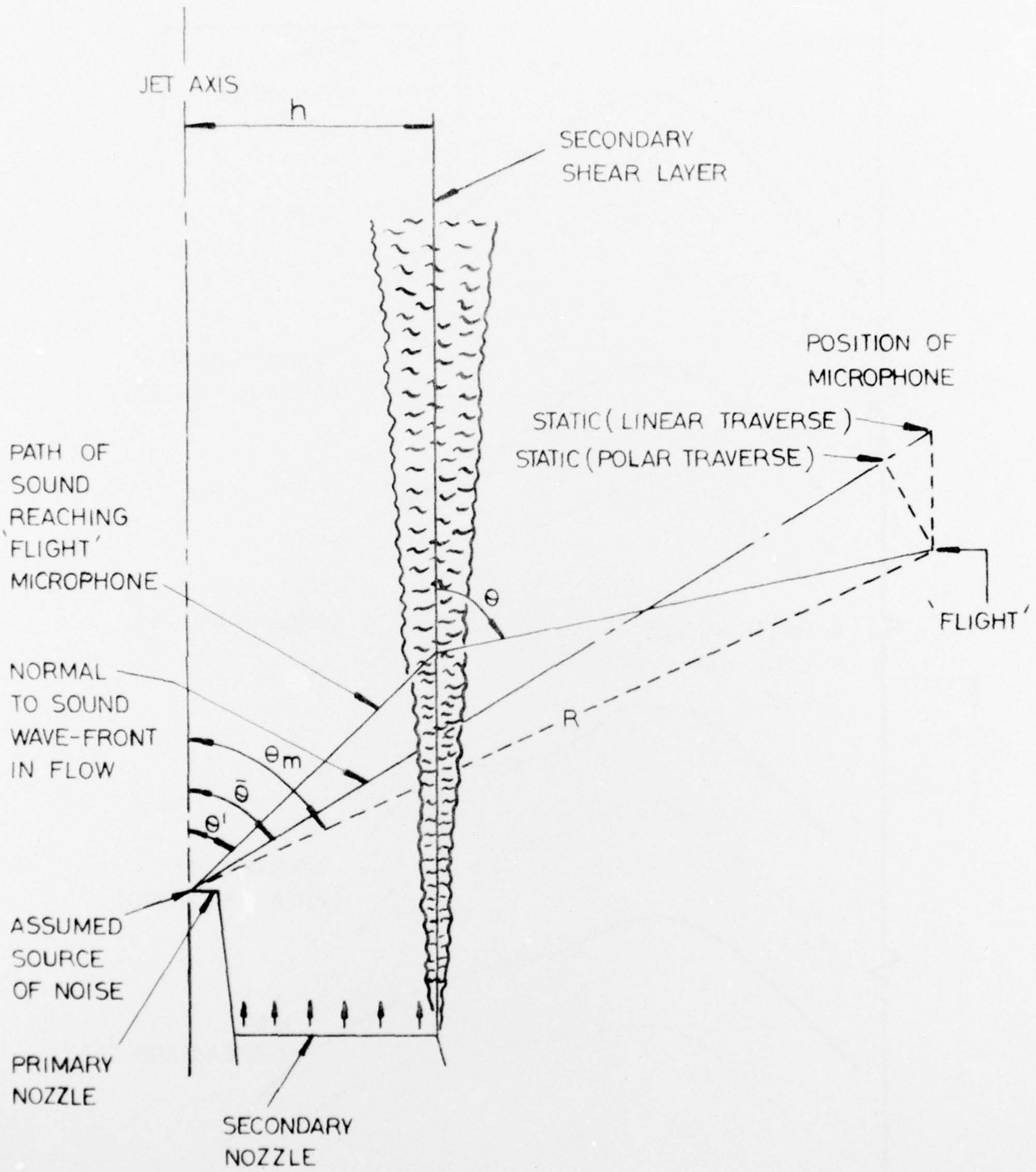


FIG.20 SOUND PROPAGATION THROUGH A SHEAR LAYER

DETACHABLE ABSTRACT CARDS

National Gas Turbine Est. Report No. 345 533.6.011.3.001.5:533.6.013.1; 532.525:534.83
1977.4
Way, D.J. and Cocking, B. J.

THE USE OF CO-FLOWING AIRSTREAMS FOR THE SIMULATION OF FLIGHT EFFECTS ON JET NOISE

The simulation of 'in-flight' effects on aircraft noise continues to be the subject of much debate. One possible simulation consists of surrounding the air jet emitted from a stationary nozzle with a concentric secondary jet blowing at an appreciably lower velocity representing that of flight. This Report describes an investigation of the influence of such a co-flowing airstream on the noise of subsonic air jets over a range of secondary-to-primary area ratios from 1.8 to 1800.

Correlations of these data have confirmed that the effects of flight on jet mixing noise may be investigated using a comparatively small secondary stream and with the microphone positioned outside the flow.

The results show that a minimum area ratio of about 50 is necessary to model adequately the effects of flight for the main noise-producing regions of the jet. As the size of the secondary stream is reduced, information for the lower frequencies is progressively lost.

P.T.O

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P.T.O

It is necessary to correct the flight data for the propagation of the sound through the shear layer surrounding the secondary flow. It has been shown that an existing theory is adequate for these corrections; this theory models the shear layer as a cylindrical velocity discontinuity and considers refraction of the sound as the dominant propagation mechanism.

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16. Descriptors (Keywords) (Descriptors marked * are selected from TEST)

Noise (sound)*; Jet engine noise*; Acoustic measurement*; Flight effects on noise

17. Abstract

The simulation of 'in-flight' effects on aircraft noise continues to be the subject of much debate. One possible simulation consists of surrounding the air jet emitted from a stationary nozzle with a concentric secondary jet blowing at an appreciably lower velocity representing that of flight. This Report describes an investigation of the influence of such a co-flowing airstream on the noise of subsonic air jets over a range of secondary-to-primary area ratios from 1.8 to 1800.

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It is necessary to correct the flight data for the propagation of the sound through the shear layer surrounding the secondary flow. It has been shown that an existing theory is adequate for these corrections; this theory models the shear layer as a cylindrical velocity discontinuity and considers refraction of the sound as the dominant propagation mechanism.